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Field Variation Characteristics of Sprayer Boom Height Using a Newly Designed Boom Height Detection System

HANJIE DOU[1,2,3], CHANGYUAN ZHAI[1,2,4], LIPING CHEN[1,2,3,4], SONGLIN WANG[1,2,3], AND XIU WANG[1,2]

[1]Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China
[2]National Engineering Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China
[3]College of Mechanical and Electronic Engineering, Northwest A&F University, Xianyang 712100, China
[4]College of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China

Corresponding author: Changyuan Zhai (zhaicy@nercita.org.cn)

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ABSTRACT To ensure boom sprayer safety and spraying efficiency, the sprayer boom height must be adjusted during pesticide application. The field variation characteristics of the sprayer boom height are the basis of the boom balance adjustment. A boom height detection system based on ultrasonic sensors was designed. Field tests were performed in 2.0 ha of vacant fields and 13.44 ha of wheat stubble fields. A signal processing method based on the K-means clustering algorithm was used to preprocess the ultrasonic sensor data. The results showed that the K-means clustering algorithm could effectively improve the detection accuracy of an ultrasonic sensor. The boom height variation was greatest at the sides of the boom, and the primary frequencies of the boom height variation were concentrated within a low-frequency band from 0 Hz to 1 Hz. The U-turn operation was more likely to cause the boom to contact the crop canopy or the ground than row operation. As the spraying speed increased, the maximum boom height variation and maximum roll angle increased; these primary components decreased in frequency, and the amplitude clearly increased. The maximum boom height variation exceeded 50 cm, and the maximum roll angle exceeded 3°, which not only aggravated the droplet drift but also caused damage to the boom and nozzles due to contact with the ground or the crop canopy. These findings can provide a theoretical basis for use in the development of an automatic boom height adjustment system.

INDEX TERMS Boom sprayer, ultrasonic sensor, boom height variation, FFT, K-means.

I. INTRODUCTION

Boom sprayers have become the primary machine type used to spray fields because they provide a better spray nozzle atomization effect, larger operation width and higher operation efficiency than other types of sprayers [1]–[3]. The boom length of sprayers generally varies from 12 to 40 m [4]. During operation, unwanted boom motions typically occur when the sprayer tyres pass over uneven terrain in the field [5], which not only affects the spraying but also may cause the boom to contact the crop canopy or the ground, resulting in serious damage to the crops and the boom [6]–[9]. To improve the uniformity of pesticide deposition and reduce droplet drift, it is crucial to monitor and adjust the height between the boom and crop canopy to maintain it at an optimum height [10]–[13].

The variation in the boom height affects the droplet distribution of boom sprayers. Speelman and Jansen [14] used acceleration sensors to perform experiments on the impact of boom height vibrations on the distribution of droplet deposition during low- and high-frequency motions of the sprayer. The experimental results showed that when the vibration frequency of the boom was reduced from 3 Hz to 0.5 Hz, the variation coefficient of the droplet distribution in the vertical plane increased by 100%. To reduce the impact of boom height variations on the spray effect, it is essential to clarify

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the characteristics of boom height variations. Research on the characteristics of boom height variations has been performed by laboratory experiments. Langenakens *et al.* [15] used experimental modal analysis to establish a dynamic model of a large boom suspension system. The results showed that a spraying height of 0.5 m or more with a fixed nozzle spacing of 0.5 m, a limited tractor speed and a low tyre pressure led to a good spray distribution with a flat fan nozzle at a top angle of 110°. Cui *et al.* [16]–[17] investigated the dynamic mechanisms of a large boom and its pendulum suspension vibration-reduction system through a movement simulation platform with six degrees of freedom to provide the theoretical basis and test method for the optimal configuration of large boom suspension parameters. The setting of the test conditions for the simulation of boom height variations in the laboratory requires the support of practical field operation data. Some field studies on boom height variation characteristics were conducted based on laboratory research. Ooms *et al.* [18] investigated the horizontal movements of trailed sprayer booms with the aim of distinguishing their yaw and jolt motions as well as their deformations. A radar speed sensor, ultrasonic sensors and accelerometers were used to extract the yaw, jolt and deformation speeds, and the corresponding test results indicated that yaw, jolting and deformation occurred near 0.3 Hz, 2 Hz and 1 Hz, respectively. Jeon *et al.* [19] installed three three-dimensional acceleration sensors and two ultrasonic sensors at the two ends and the middle of an instrumented self-propelled sprayer with a 27 m boom to measure the boom height variations. The test results showed that the mean peak boom end height ranged from 1.12 m to 2.02 m (half tank load) and from 1.48 m to 1.93 m (empty tank). Wang *et al.* [20] designed an automatic boom height adjustment control system. The field testing of this system showed that the roll angle of the boom could reach 3° without height adjustment at an operating speed of 3 km/h and that the variation coefficient of pesticide deposition could reach up to 30%. Cui *et al.* [21] measured the boom roll and vibration acceleration along the vertical direction by installing an ultrasonic sensor and an acceleration sensor at the end of the boom. The test results showed that the rolling and swaying of the boom was the primary form of movement that affected the distribution of droplet deposition in the field.

Currently, research on boom height variations during operation focuses mainly on laboratory or small-scale field tests. The boom height variation characteristics of the row and U-turn operations of large-scale field tests have not been studied in detail. However, the boom height variation characteristics obtained through laboratory and field experiments provide a theoretical basis for boom structure optimization and research on a boom height balance control algorithm. Some boom height adjustment algorithms have been proposed based on the boom height variation characteristics [22]–[25]. These algorithms perform well when driving at moderate speeds over large plains with flat terrain and large areas of cultivated land, but they are not suitable for high speeds or hilly environments. The complex farmland ground environment requires a rapid response of the boom height adjustment system. The response performance of a boom height adjustment system can be improved by a boom height detection system and hydraulic control system. The hydraulic control system is affected by the characteristics of the hydraulic oil source and components, and the system response performance cannot easily be improved. However, the boom height detection system can significantly improve the system response performance of the signal processing algorithm of the boom height detection sensor. At present, ultrasonic sensors are primarily used for boom height measurements. Research on signal processing algorithms for ultrasonic sensors is insufficient. A fast and stable signal processing algorithm for a boom height detection sensor is lacking, which is not conducive to the development of a boom adjustment system suitable for high speeds or complex terrain environments.

In this study, a new boom height detection system based on ultrasonic sensors, global position system (GPS) and controller area network (CAN) buses was designed. The system can obtain and record the boom height variation data and integrate with the hydraulic power system for further development of an automatic boom height adjustment system. Simultaneously, an ultrasonic sensor signal processing method based on the K-means clustering algorithm was proposed. Compared with existing signal processing algorithms, it has a fast processing speed and can effectively reduce the influence of external interference on ultrasonic sensor detection. This method could be used to develop a boom adjustment system suitable for high speeds or complex terrain environments. Large-scale field tests based on the boom height detection system were carried out. The boom height variation characteristics of the row and U-turn operation were studied in detail. The results will be instructive in developing an automatic boom height adjustment system.

The rest of this article is organized as follows. Section II provides the boom height detection system design, field test design and data processing methods. Section III presents the field test results and discusses the results. Section IV concludes this article. Section V discusses future research directions based on the bottlenecks faced during this study.

II. MATERIALS AND METHODS

A. BOOM SPRAYER

A 21 m boom sprayer (3W-VRT4, Beijing Research Center of Intelligent Equipment for Agriculture, China) was used in the field tests. The boom was divided into three sections: the left section, the middle section and the right section. The left and right sections were controlled by hydraulic cylinders. The sprayer was connected to a tractor through a three-point suspension, and the rear power take-off shaft of the tractor was connected to the diaphragm pump to power the spray system. An ultrasonic sensor was fixed on each section of the boom to monitor the boom height variation in real time.

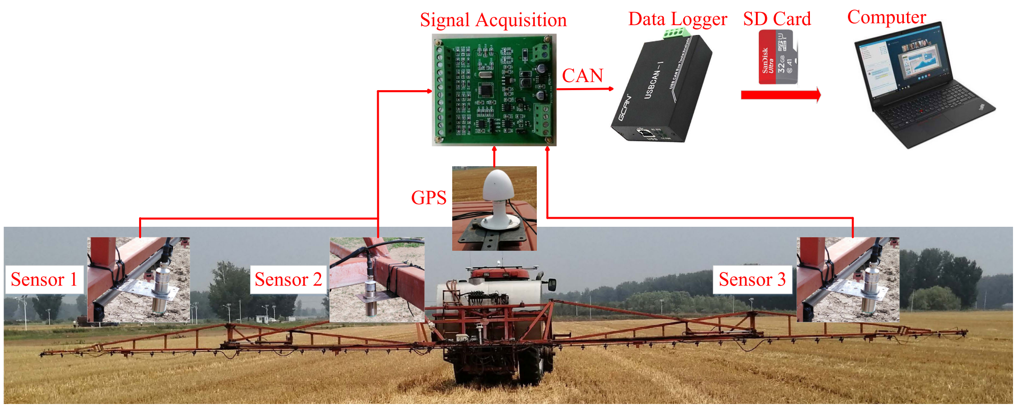


FIGURE 1. Sprayer boom height detection system architecture.

The GPS receiver was placed at the centre of the tractor to record the spray trajectory in real time (Fig. 1).

B. DESIGN OF THE BOOM HEIGHT DETECTION SYSTEM

The boom height detection system was designed to monitor the boom height variation (Fig. 1). The detection system was composed of a data acquisition unit (self-developed by the Beijing Research Center of Intelligent Equipment for Agriculture), three ultrasonic sensors (WUB2000-30GM75-1-V15, Guangzhou Weiheng Electronics Corporation, China), a GPS receiver (TOP102, Shenzhen Shidaotong Electronic Technology Corporation, China), and a data logger (USBCAN-I, Shenyang Guangcheng Technology Corporation, China). The data acquisition unit has 3 channels of analogue input from 4 mA to 20 mA and supports serial port and CAN bus communication.

The GPS receiver communicates with the data acquisition unit through the serial port, and the data logger communicates with the data acquisition unit via the CAN bus. The CAN bus will facilitate integration with the hydraulic power system for the further development of the boom height automatic adjustment system based on the CAN bus. The measurement range of the ultrasonic sensors is 0.1 m to 2 m, which corresponds to 4 mA to 20 mA in terms of the sensor output current. The data acquisition rate and operating frequency of the ultrasonic sensors are 100 Hz and 180 kHz, respectively. The baud rate and positioning update frequency of the GPS receiver are 11520 Hz and 10 Hz, respectively.

The working flow chart of the boom height detection system is shown in Fig. 2. After the system is powered on, the data acquisition unit determines whether the GPS receiver is ready for positioning. Once successfully positioned, the GPS receiver and ultrasonic sensors of the left, middle and right sections output the GPS position information and current signals in real time, which are analysed to obtain the GPS latitude, longitude and boom height information. If those data are valid, they are converted into the CAN data format to be transmitted to the CAN bus analyser through the CAN bus. The CAN bus analyser stores the CAN data in Excel file format for subsequent data analysis.

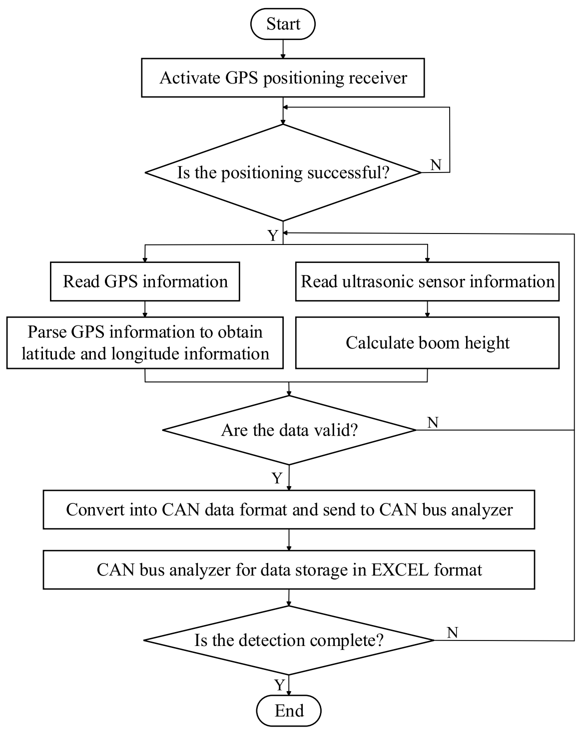
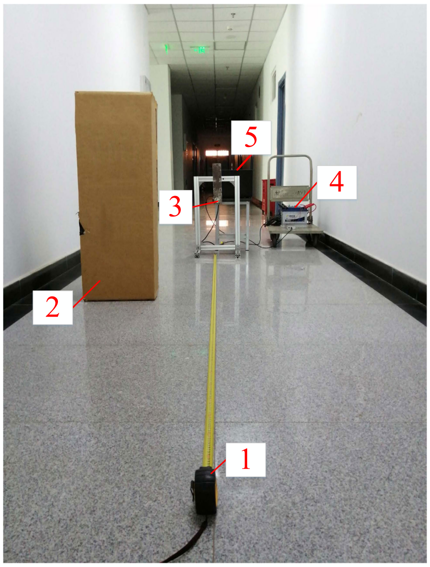


FIGURE 2. Flow chart of the boom height detection system.

C. SENSOR CALIBRATION

The ultrasonic sensors were calibrated (Fig. 3). The ultrasonic sensor was placed in an open area without any obstructions, the personal computer (PC) and CAN bus analyser were connected through the USB serial port, and the PC software interface displayed the output current signals of the ultrasonic sensor in real time. A carton was the object to be detected in this test, and a tape measure was placed straight below the line of the beam of the ultrasonic sensor to measure the moving distance of the carton. The carton moved at 0.1 m intervals from 0.1 m to 2 m, and the corresponding current output signal was recorded. Each measurement was repeated 3 times, and the average of 3 measurements was used to establish the



1. Tape measure, 2. carton, 3. ultrasonic sensor, 4. power and data, acquisition module and 5. PC

FIGURE 3. Ultrasonic sensor calibration experiment.

relationship equation between the detection distances and the output currents.

D. FIELD TEST DESIGN

After wheat harvest, it is necessary to apply pesticides to control weeds before new crop planting. During spraying, a variation in the boom height not only affects the spray effect but also may cause damage to the boom and nozzles if the boom contacts the ground or wheat stubble. To explore the characteristics of the boom height variation and the reliability and stability of the boom height detection system during spraying in a wheat stubble field, field tests were conducted in a 2 ha vacant field and 13.44 ha wheat stubble field. The tests consisted of detection tests at different speeds and field-scale tests. In the detection tests at different speeds, to compare the boom height variation characteristics of the vacant field and wheat stubble field at different speeds, the sprayer operated according to the trajectory shown in Fig. 4a and the red trajectory in Fig. 4b, respectively. The west stubble area with the red track was larger than the other stubble areas, which ensured that the test was performed over a complete area and avoided the impact on the boom height variation at the junction. The red trajectory is the wheat stubble field close to the vacant field. The topography variation in the wheat stubble field is basically the same as that in the vacant field, which can reduce the impact of the topography variation on the boom height variation. The Chinese standard GB/T 20183.3-2006 "Equipment for crop protection - Spraying equipment - Part 3: Test methods for volume/hectare adjustment systems of agricultural hydraulic pressure sprayers" is considered, which requires that the speed during the test be 1.5 m/s to 2.5 m/s, and studies have usually sprayed at a moving speed of 1.9 m/s in recent years [26]. The sprayer was operated at speeds of 1.5 m/s, 2.0 m/s and 2.5 m/s. During the field-scale test, wheat stubble heights of 15 cm, 20 cm, 25 cm and 35 cm were set (Fig. 4b). The test was performed at a speed of 1.9 m/s from west to east along the black and red trajectories.

The sprayer carried a half tank of water. The recommended spraying heights were 40 cm and 50 cm above the crop [9]. When the height of the nozzles from the ground is set to 40 or 50 cm, the boom field height variation might cause damage to the boom and nozzles through contact with the ground or the crop canopy. The nozzle height of 110 cm is almost the maximum setting for the boom, which can ensure that the sprayer boom is not damaged during the spraying operation. The height of the nozzles to the ground was set to 110 cm, and the emitting surface of the ultrasonic sensor was placed at the same height as the nozzle surface. The tests were conducted at the National Experiment Station for Precision Agriculture, Beijing. All the tests were repeated 3 times, and the boom height variation was recorded.

E. ACCELERATION DATA PROCESSING

The variation in boom height between the left and right sections causes boom tilt, which will influence pesticide deposition. The boom tilt can be evaluated using the roll angles of the boom. Assuming that the ground below the boom is flat, equation (1) can be used to calculate the roll angles of the boom, which indicate the boom height variation.

$$\theta = \arcsin \frac{H_1 - H_2}{L} \tag{1}$$

where H_1 is the distance from ultrasonic sensor 3 to the ground, in m; H_2 is the distance from ultrasonic sensor 1 to the ground, in m; and L is the width of the boom, in m.

The fast Fourier transformation (FFT) technique was applied to the boom height variation data to isolate the frequency components for analysis. The boom height variation data were divided into 100 millisecond intervals consisting of 3000 points. Zero padding was used to increase the number of points to 3072 before the FFT was applied to each interval [27]. The primary frequency and amplitude were obtained using MATLAB®R2016b (MathWorks, USA) software. ArcGIS (Environmental Systems Research Institute, USA) software was used to analyse the GPS position and boom height variation information and show the boom height variation in field-scale tests with wheat stubble.

The K-means clustering algorithm was used to process the ultrasonic sensor detection data. The algorithm first selects k objects at random from data objects as the initial clustering centres, calculates the distance between each object and these central objects according to the mean value of each clustering object, and re-divides the corresponding objects according to the minimum distance. Then, the algorithm re-calculates the average of each cluster. This process is repeated until each cluster no longer changes [28], [29]. Usually, the criteria for the K-means algorithm use the squared error criterion

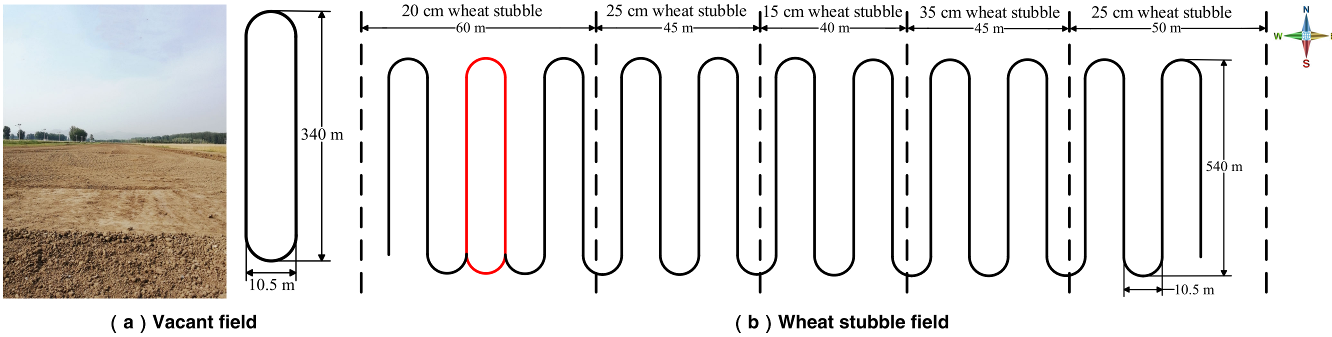


FIGURE 4. Experimental scheme.

TABLE 1. Variations in boom height in vacant and wheat stubble fields.

Field tests	Speed m/s	The boom height variation, cm					
		Left section		Middle section		Right section	
		Maximum	Average	Maximum	Average	Maximum	Average
Vacant field	1.5	61.9	15.0	9.1	2.3	76.1	22.3
	2.0	72.3	14.6	9.5	2.1	89.9	24.4
	2.5	72.9	15.5	10.2	2.3	98.4	23.3
Wheat stubble field	1.5	60.2	16.2	17.4	4.0	67.4	16.3
	2.0	59.5	16.2	26.5	3.0	71.3	18.0
	2.5	76.7	18.4	35.4	4.3	89.9	20.5

function, as defined as:

$$E = \sum_{i=1}^{k} \sum_{x \in C_i} |x - \overline{x_i}| \quad (2)$$

where E is the sum of the squared error in the data set of all the ultrasonic sensor detection values, C_i is the cluster of ultrasonic sensor detection values, x is the ultrasonic sensor detection value, and x_i is the average value of cluster C_i. k is the number of clusters.

The flow chart of the boom height calculation based on the K-means clustering algorithm is shown in Fig. 5. During the working process, the boom height detection system reads the 3 ultrasonic sensor signals in real time, and it first judges the validity of the sensor detection signal. If the detection signal is abnormal, it will judge whether the sensor has entered the blind zone. Once the ultrasonic sensor has entered the blind zone, the system will send a data exception command. Otherwise, the system will convert the obtained data into boom height values every 1 s and store them in an array form and then call the K-means clustering algorithm to preprocess the acquired boom height detection data, ultimately obtaining accurate boom height detection values.

III. RESULTS AND DISCUSSION

A. SENSOR CALIBRATION

The detection distances and output currents of the ultrasonic sensors on the left, middle and right sections were analysed, and the three fitting relationship curves are shown in Fig. 6. Equations (3), (4) and (5) are the relational expressions of the fitted straight lines, and the R^2 values were 0.9995, 0.9989 and 0.9960, respectively. The linearities of the three ultrasonic sensors were good and met the operating requirements.

$$y = 11.693x - 31.878 \quad (3)$$
$$y = 11.713x - 31.975 \quad (4)$$
$$y = 11.235x - 20.881 \quad (5)$$

where x is the output current, in mA, and y is the detection distance, in cm.

B. DETECTION TEST AT DIFFERENT SPRAYING SPEEDS

The time analysis results from the vacant field and the wheat stubble field are shown in Figs. 7 and 8. The results showed that the variations in the boom height of the left and right sections had good symmetry at different speeds. The maximum and average values of the boom height variation (the distance between the emitting surface of the ultrasonic sensor and the test surface) are listed in Table 1. The results indicated that the boom height variations of the two fields were similar but that the boom height variation in the vacant field was larger than that in the wheat stubble field. The greatest boom height variations primarily occurred in the left and right sections, but the boom height variation in the middle section varied slightly. As the moving speed increased, the boom roll amplitudes increased. The maximum boom height variations of the left, middle and right sections in the vacant field were 72.9 cm, 10.2 cm and 98.4 cm, respectively, and those in the wheat stubble field were 76.7 cm, 35.4 cm and 89.9 cm, respectively.

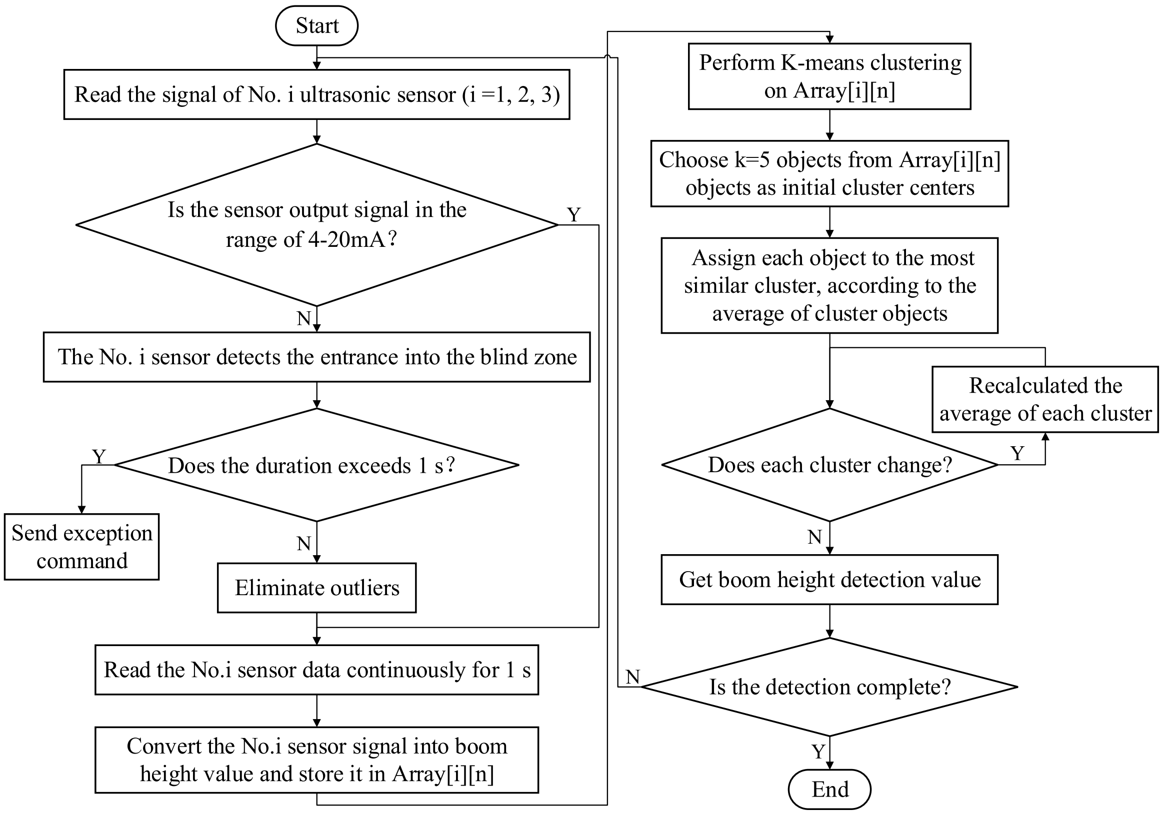


FIGURE 5. Flow chart of boom height calculation based on the K-means clustering algorithm.

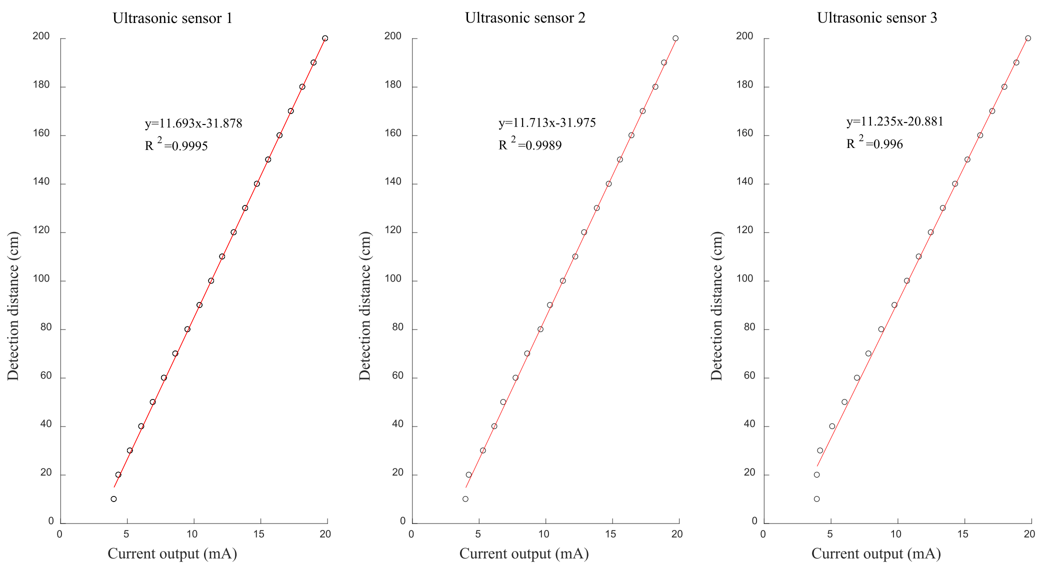


FIGURE 6. Ultrasonic sensor calibration curves.

The roll angles of the boom at different speeds are shown in Fig. 9. The results showed that the roll angles were affected by the moving speeds in the vacant field and the wheat stubble field. As the moving speed increased, the roll angles of the boom increased. The maximum roll angles in the vacant field at speeds of 1.5 m/s, 2.0 m/s and 2.5 m/s were 3.27°, 3.29°, and 3.78°, respectively, and those in the wheat stubble field were 3.15°, 3.16°, and 3.40°, respectively.

The results of the FFT analysis on the boom height variation in the vacant field and wheat stubble field are shown in Figs. 7 and 8. The primary frequencies were

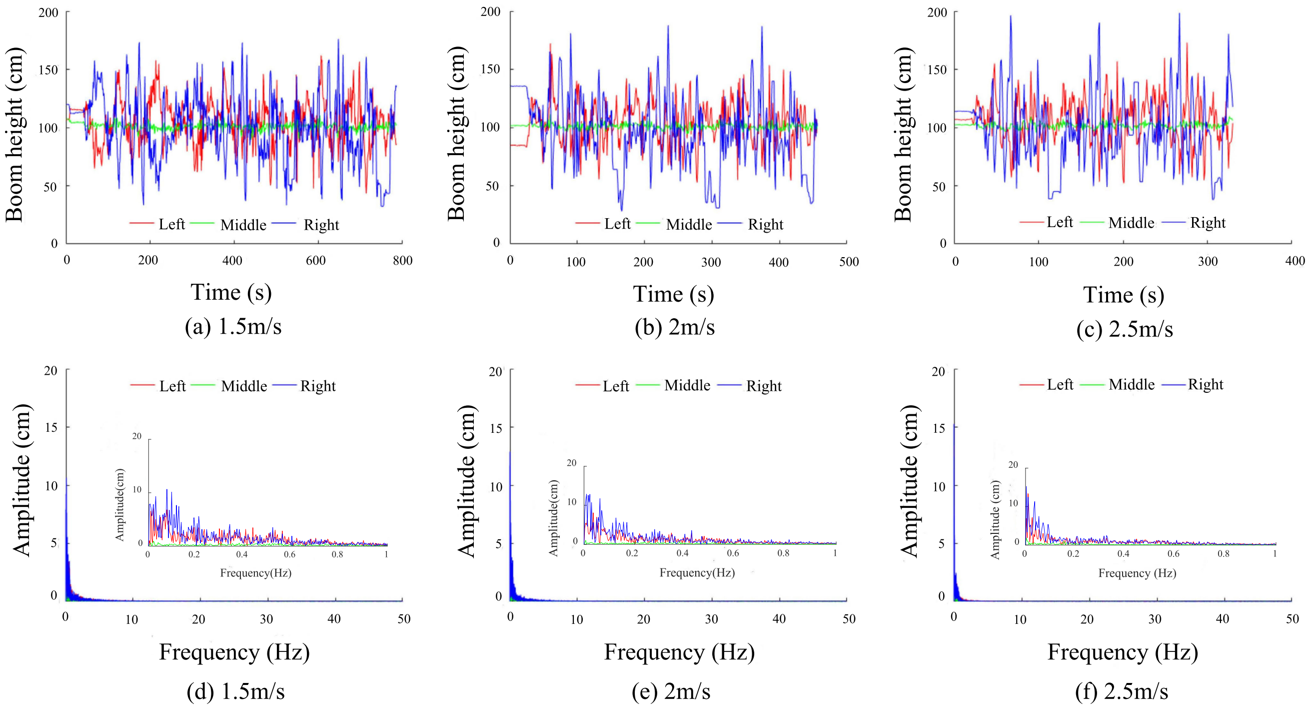


FIGURE 7. Time and frequency domain diagrams of the variation in boom height in the vacant field.

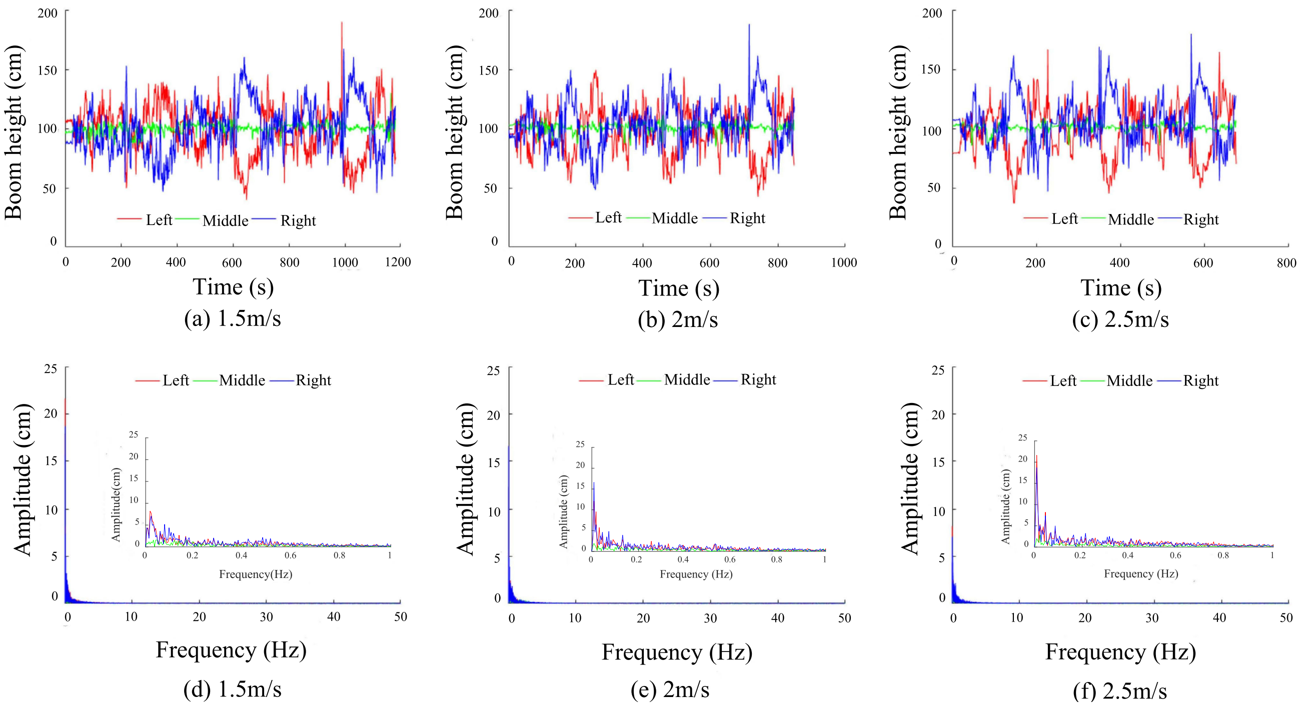


FIGURE 8. Time and frequency domain diagrams of the variation in boom height in the wheat stubble field.

concentrated in a low-frequency band from 0 Hz to 1 Hz. These primary components decreased in frequency with increasing moving speed. However, the amplitude clearly increased when the spraying speed increased. The primary frequencies of the variation in boom height at the left, middle and right sections are listed in Table 2. At different speeds, the primary frequencies of the boom height variation in the vacant field were greater than those in the

TABLE 2. Primary frequencies and amplitudes of the variations in boom height in vacant and wheat stubble fields.

Field tests	Speed m/s	Left section		Middle section		Right section	
		Frequency Hz	Amplitude cm	Frequency Hz	Amplitude cm	Frequency Hz	Amplitude cm
Vacant field	1.5	0.077	10.7	0.020	0.9	0.077	6.8
	2.0	0.010	12.9	0.007	1.0	0.037	8.1
	2.5	0.003	15.3	0.003	1.9	0.010	13.4
Wheat stubble field	1.5	0.020	7.1	0.045	1.6	0.018	8.2
	2.0	0.009	16.6	0.009	1.9	0.009	12.1
	2.5	0.009	21.6	0.009	2.0	0.009	18.7

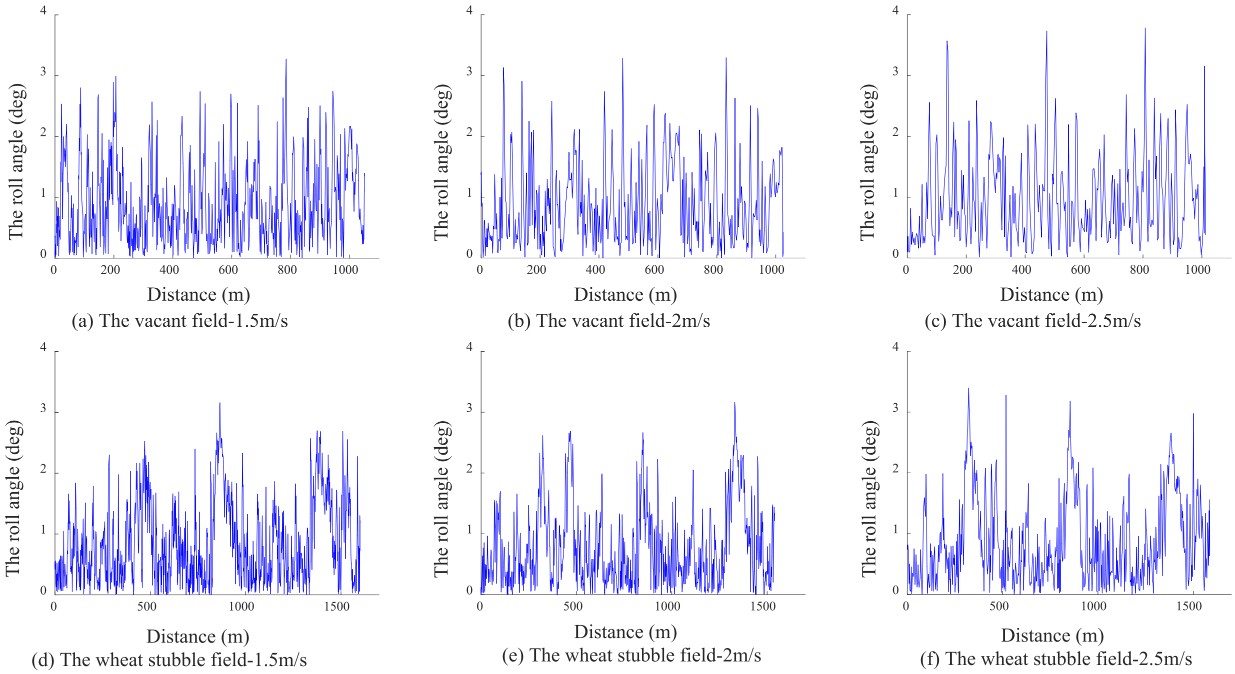


FIGURE 9. Roll angles of the boom at different speeds.

wheat stubble field. The primary frequencies of the boom height variations of the left, middle and right sections in the wheat stubble field were all 0.009 Hz at speeds of 2.0 m/s and 2.5 m/s.

C. FIELD-SCALE TEST

A boom height variation distribution map was generated (Fig. 10). The data points for the left, middle and right trajectories along the moving direction represent the boom height variations of the left, middle and right sections, respectively. The results showed that the boom height detection system was stable, and it could be used for the real-time monitoring of the boom height variation. This variation primarily occurred on the sides, and the boom height of the middle section varied only slightly. The boom height variation in the left and right sections during U-turn operation was greater than that during row operation. The maximum and average roll amplitudes of the boom (the boom height difference between the left and right sections) during U-turn operation were 126.1 cm (corresponding to a roll angle of 3.4°) and 57.8 cm, respectively. The maximum and average roll amplitudes of the boom during row operation were 114.1 cm (with a corresponding roll angle of 3.1°) and 34.2 cm, respectively. The boom height variation during U-turn operation was greater than that during row operation. The U-turn operation was more likely to cause the boom to contact the crop canopy or the ground, resulting in boom and nozzle damage. The detection value of the ultrasonic sensor for the left and middle sections was abnormal at the position indicated by the red circle in Fig. 10. The boom height of the left and middle sections was greater than 156 cm, and the boom height of the right section was less than 71 cm. This pattern did not conform to the normal rolling pattern of the boom.

The detection value of different stubble heights was classified through the K-means clustering algorithm. The ultrasonic sensors of the left and right sections were fixed on the top of the boom, and the boom heights in those sections varied greatly. The ultrasonic sensor of the middle section was fixed in the middle of the boom, and the boom height

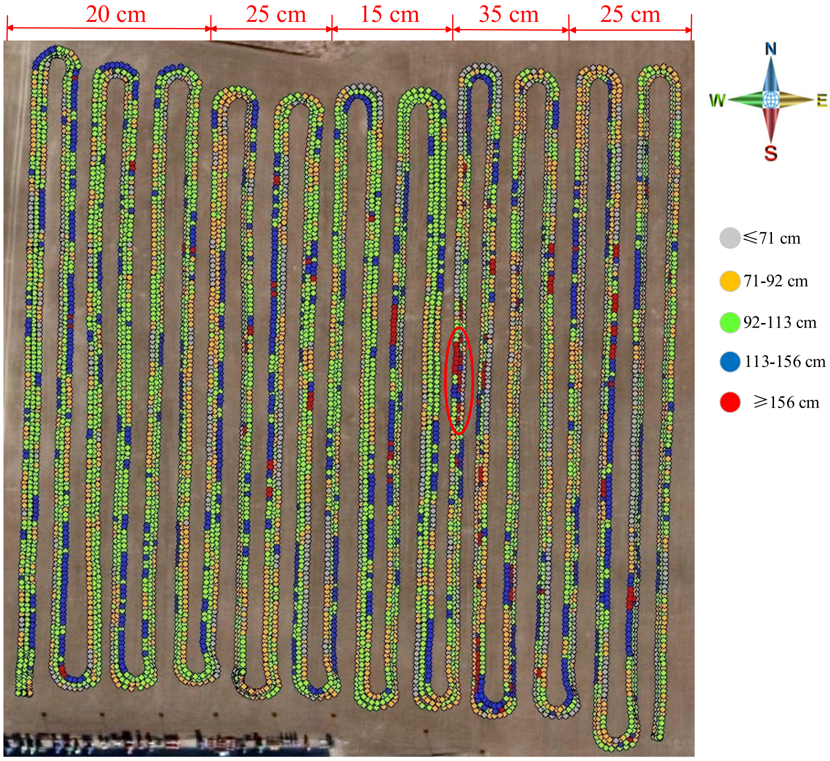


FIGURE 10. Distribution map of boom height variation in a wheat stubble field.

in that section varied slightly. The ultrasonic sensor of the middle section was less affected by the boom vibration, and the primary source of the variation in the detection signal was the change in the stubble height. However, the variation in the detection signal of the ultrasonic sensors on both sides was caused not only by the change in the stubble height but also by the considerable boom vibration. Therefore, the wheat stubble heights were calculated to evaluate the effect of the clustering algorithm using the cluster analysis of the boom height variation data for the middle section. The wheat stubble heights of the field-scale test were 15 cm, 20 cm, 25 cm and 35 cm, at which an ultrasonic sensor might be able to detect the ground where the canopy was sparse or unshrouded. The primary detection positions of the ultrasonic sensor were the stubble canopy surface at 15 cm, 20 cm, 25 cm and 35 cm and the ground. The data were divided into 5 categories, and the differences between the clustering values and actual wheat stubble heights could be used to evaluate the effect of the K-means clustering algorithm at different wheat stubble heights. The cluster analysis results are shown in Fig. 11. The results showed that the detection values of the ultrasonic sensors spanned different categories at the same wheat stubble height, which might be caused by the uneven crop canopy or the rough ground under the boom. The clustering centre point values of each category were 104.3 cm, 99.5 cm, 95.3 cm, 89.2 cm and 81.2 cm. The heights of the ground and different stubble canopies to the emitting surface of the ultrasonic sensor were 100 cm, 95 cm, 90 cm, 85 cm and 75 cm. The differences between the above two sets of values were 4.3 cm, 4.5 cm, 5.3 cm, 4.2 cm and 6.2 cm. The average boom height variation in the middle section was 5.4 cm. Considering the impact of the boom height variation, the clustering centre point values of each category were used as the actual heights of the boom to the crop canopy. The clustering errors were 1.1 cm, 0.9 cm, 0.1 cm, 1.2 cm and 0.8 cm. Thus, the K-means clustering algorithm could effectively distinguish the different heights of the stubble canopy.

D. DISCUSSION

During the wheat harvest, the height of the harvester header can be adjusted according to terrain changes, and wheat stubble heights change within only a small range. The detection position of the ultrasonic sensors was the surface of the wheat stubble canopy, and the irregularity of the ground had little effect on the detection performance of the ultrasonic sensor. However, the irregularity of the ground was detected by the ultrasonic sensor in the vacant field, which was probably the reason why the boom height variation in the vacant field was greater than that in the wheat stubble field. During the early stage of crop planting, due to the small size of the crops, the ultrasonic sensor detection values will be affected by ground irregularities. Therefore, different signal processing algorithms should be considered in the development of an automatic boom height adjustment system.

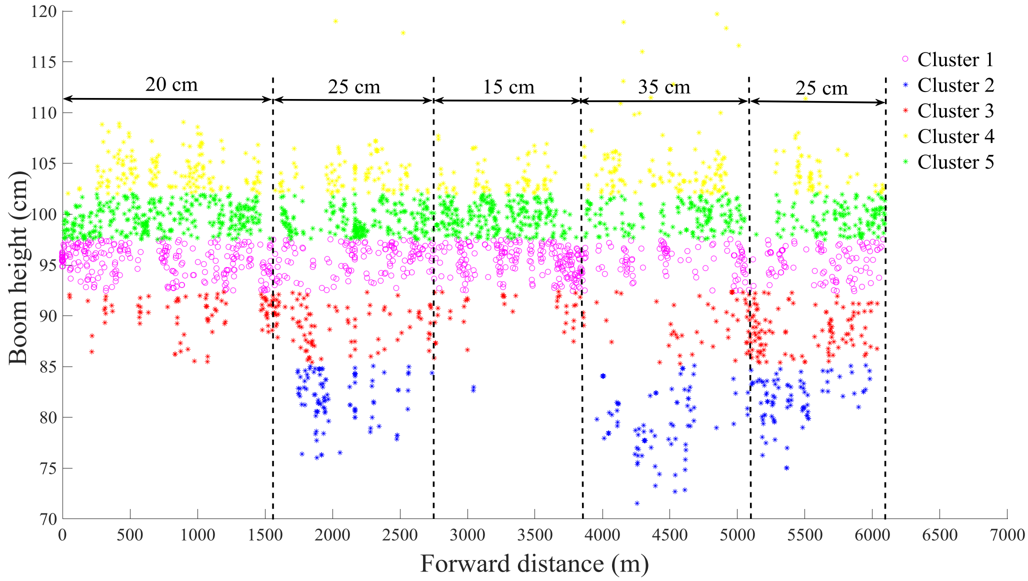


FIGURE 11. K-means clustering diagram of the boom height variation.

The maximum boom height variations of the left and right sections exceeded 50 cm. The literature showed that the recommended spraying heights were 40 cm and 50 cm above the crop, while raising the boom height to above 50 cm considerably increased the drift potential [8], [12], [30]. The maximum boom height variations of the left and right sections in both the vacant field and wheat stubble field exceeded the recommended spraying heights, which not only aggravated droplet drift but also caused damage to the boom and nozzles due to contact with the ground or crop canopy. Thus, it is necessary to adjust the boom height during spraying. The maximum roll angles of the boom in the vacant field and wheat stubble field exceeded 3° at the tested speeds. The literature showed that when the roll angle of a boom reached 3°, the variable coefficient of pesticide deposition increased to 30%. The variable coefficient of pesticide deposition for normal spraying operations should be less than 10%, and a variable coefficient of greater than 15% indicated that the boom settings were not appropriate for pesticide application [20], [31], [32]. This finding further illustrated the importance of boom height adjustment.

The primary frequencies of the boom height variation were different in the vacant field and wheat stubble field. The corresponding primary frequencies of the vacant field were greater than those of the wheat stubble field. However, the boom height variation in the vacant field was larger than that in the wheat stubble field. The primary frequency of the boom height variation was related to the magnitude of the boom height variation. The greater the boom height variation was, the smaller the primary frequency of the boom height variation, and the more violent the boom rolling. The primary frequencies of the boom height variations of the left, middle and right sections were primarily concentrated from 0 Hz to 1 Hz. The other frequencies of the boom height variation were generally small, from 1 Hz to 50 Hz. The literature showed that boom yawing, jolting and deformation occurred at approximately 0.3 Hz, 2 Hz and 1 Hz, respectively (the corresponding tests were performed on trailed sprayers equipped with 22 m and 24 m boom lengths on different soils) [18]. The boom height variation could be considered to be primarily boom yawing over the range from 0 Hz to 1 Hz and boom jolting and deformation from 1 Hz to 50 Hz. However, when the speed was greater than 2 m/s, the primary frequencies of the boom height variations of the left, middle and right sections were the same in the wheat stubble field, reaching the minimum frequencies for boom yawing. The minimum frequency of boom yawing reached 0.009 Hz in wheat stubble fields. These findings can provide a reference for laboratory simulation experiments and for developing signal processing algorithms for ultrasonic sensors.

An abnormal detection value by the ultrasonic sensors at the left and middle sections might be due to the slope of the terrain, which would cause the ultrasonic sensor to enter a blind zone, resulting in abnormal detection results. This situation should be considered when developing an automatic boom height adjustment system. This situation can be judged by the variation in the boom height of the middle section. The boom height data for this section could be used as a reference for the boom height adjustment of the left and right sections.

During wheat harvesting, the height of the stubble is uneven, which will interfere with the detection of the ultrasonic sensor. The K-means clustering algorithm could distinguish the stubble canopy of different heights well. However, when the canopy was sparse or unshrouded, the ultrasonic sensor detected the ground. At this time, if the boom height is adjusted based on the ground detection value of the ultrasonic sensor, damage may occur to the boom and nozzles by contact with the stubble canopy. This phenomenon could be avoided

TABLE 3. Comparison of boom height detection methods.

Sensor type	Detection index	Signal processing methods	Advantage	Disadvantage	References
Ultrasonic sensor	Boom height	Limit filtering, data smoothing and data fusion algorithm based on optimal weight	Effectively reduces the influence of external interference on ultrasonic sensor detection	Need to manually input the average height of the crop; complex implementation process	Cui L F et al. [22]
Ultrasonic sensor	Boom height	Reduce the interference of cotton branches and leaves on ultrasonic sensor detection by setting the threshold	Easy implementation and effective reduction in interference	Need to select a suitable threshold	Wei X H et al. [4]
Touch Sensor	Boom height	Detect boom height by contact rod deformation	Fast response and less external interference	When used in the field after seeding, the sensor contact rod will damage the crop	Wang S L et al. [20]
Lidar sensor	Boom height	Measure the change in the displacement of the boom by marking the position of the laser point on the receiving board	High measurement accuracy	Only the height of the boom relative to the marking plate can be detected, while the height of the boom and the ground or canopy cannot be detected	Cui L F et al. [21] Ooms et al. [18]
Tilt sensor	Boom tilt angle	The change in the height of the boom can be calculated using the boom tilt angle	The tilt angle of the boom can be obtained directly	The boom height cannot be directly obtained, and it has a high installation requirement	Qiu B J et al. [33] Cui L F et al. [23]
Acceleration sensor	Boom displacement	Obtain the boom height change by analysing the vertical and horizontal acceleration of the boom	The vibration frequency and vertical and horizontal vibration displacement of the boom can be obtained	The spray boom relative to the crop canopy height cannot be directly obtained, and it has a high installation requirement	Herbst et al. [34] Jeon et al. [19] Ooms et al. [18]
Ultrasonic sensor	Boom height	The K-means clustering algorithm	Fast processing speed and easy implementation; effectively reduces the influence of external interference on ultrasonic sensor detection	The number of clusters K needs to be determined	This paper

by developing a boom height adjustment algorithm based on the clustering results. Therefore, the K-means clustering algorithm could be used to reduce the influence of the stubble height and improve the stability of an automatic boom height adjustment system. Preprocessing the ultrasonic sensor data in this way could provide a signal processing method for use in the development of an automatic boom height adjustment system. Table 3 compares the advantages and disadvantages of this method compared to the existing methods.

IV. CONCLUSION

1) A boom height detection system based on ultrasonic sensors, GPS and CAN buses was designed. In this system, the boom height variation data were obtained, recorded and integrated with the hydraulic power system for further development of an automatic boom height adjustment system based on the CAN bus.

2) The tests in a vacant field and wheat stubble field showed that the boom height variation was greatest on the left and right sides, while the height of the boom in the middle section varied slightly at moving speeds of 1.5 m/s, 2.0 m/s and 2.5 m/s. As the speed increased, the boom height variations and maximum roll angles of the boom increased. The maximum boom height variations of the left and right sections exceeded 50 cm, and the maximum roll angles of the boom exceeded 3°, which not only aggravated droplet drift and reduced pesticide deposition but also caused damage to the boom and nozzles due to contact with the ground or crop canopy. It is necessary to adjust the boom height during the spraying operation. The field-scale tests showed that the boom height variations of the left and right sections during U-turn operation were even greater than that during row operation. The U-turn operation was more likely to cause the boom to hit the crop canopy or the ground, resulting in boom and nozzle damage.

3) The results of the FFT analysis of the boom height variation in vacant and wheat stubble fields showed that the primary frequencies were concentrated in a low-frequency band from 0 Hz to 1 Hz. These primary components decreased in frequency with increasing moving speed.

However, the amplitude clearly increased when the spraying speed increased. The frequency variations of the left, middle and right sections were primarily caused by boom yawing over a range from 0 Hz to 1 Hz, and boom jolting and deformation occurred from 1 Hz to 50 Hz. The minimum frequency of boom yawing might be 0.009 Hz in wheat stubble fields.

4) The K-means clustering algorithm was used to analyse the boom height variation in the middle section during the field-scale tests. The results showed that the clustering centre point values of each category could be used as the actual height of the boom to the crop canopy. The K-means clustering algorithm could be used to preprocess the ultrasonic sensor data, which would provide a signal processing method for the development of an automatic boom height adjustment system. Simultaneously, the boom height data of the middle section could be used as a reference for the boom height adjustment of the left and right sections.

V. FUTURE WORK

(a) The sampling frequency of ultrasonic sensors is limited, resulting in low sampling data of boom height detection systems in high-speed operation. The number of sampled data affects the K-means clustering effect. More sampling points can be obtained on valid detection data by improving the response performance of ultrasonic sensors and developing new data processing algorithms.

(b) The primary frequencies of the boom height variation were concentrated within a low-frequency band from 0 Hz to 1 Hz. The noise during spraying will generate high-frequency components for the ultrasonic sensor detection signal. The high-frequency components could be filtered to improve the signal processing speed. The corresponding software and hardware filtering methods should be further studied.

(c) As the moving speed increases, the detection lag of the ultrasonic sensor increases. Increased detection lag will affect the boom height follow-up adjustment. The lag compensation algorithm should be added to the boom height adjustment system to improve the boom height following the control effect.

In future work, a boom height balance control system could be developed based on the detection system designed in this article. Universal tests of boom height control for different crop canopies at different stages should be conducted. In addition, high-speed performance tests of the boom height balance control system also need to be performed.

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HANJIE DOU received the B.S. degree in mechanical and electrical engineering from Northwest A&F University, Shaanxi, in 2014, and the M.E. degree in mechanical engineering from the China University of Petroleum, Beijing, in 2017. He is currently pursuing the Ph.D. degree in agricultural electrification and automation with Northwest A&F University. His current research interests include precise variable spraying, precise variable fertilization, and agricultural robotics.

CHANGYUAN ZHAI received the B.S. degree in electronic information science and technology from the Xi'an University of Technology, Xi'an, Shaanxi, in 2004, the M.E. degree in control theory and control engineering from Xi'an Jiaotong University, Xi'an, in 2007, and the Ph.D. degree in agricultural mechanization engineering from Northwest A&F University, Shaanxi, in 2012. He is currently a Professor with the National Engineering Research Center of Intelligent Equipment for Agriculture, Beijing. His main research interests include precision agriculture and agricultural intelligent equipment technology.

LIPING CHEN received the M.S. and Ph.D. degrees in crop cultivation and tillage from China Agricultural University, Beijing, in 1998 and 2003, respectively. She is currently a Professor with the National Engineering Research Center of Intelligent Equipment for Agriculture, Beijing. Her main research interests include precision agriculture and the agricultural Internet of Things technology.

SONGLIN WANG received the B.S. degree in mechanism design, manufacturing, and automatization from the Liaoning University of Technology, Jinzhou, Liaoning, in 2011, and the M.E. and Ph.D. degrees in agricultural mechanization engineering from Northwest A&F University, Yangling, Shaanxi, and Beijing Research Center of Intelligent Equipment for Agriculture, Beijing, from 2012 to 2020. He is currently an Associate Professor with the Liaoning University of Technology. His current research interest includes precise variable spraying.

XIU WANG received the B.S. degree in agricultural mechanization engineering from the Agricultural University of Hebei, Baoding, Hebei, in 1987, and the Ph.D. degree in agricultural electrification engineering from China Agricultural University, Beijing, in 2000. He is currently a Professor with the National Engineering Research Center of Intelligent Equipment for Agriculture, Beijing. His main research interests include precision agriculture and agricultural intelligent equipment technology.