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Research On The Relative Crop Canopy Height Detection System Of Sprayer Boom Based On Lidar

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Abstract:
In order to meet the demand of precision spraying operation of boom sprayer, a system for detecting the height of sprayer boom relative to the top of crop canopy using low-cost two-dimensional laser radar was developed in this paper. The detection system converts the data from the radar polar coordinate system to the two-dimensional rectangular coordinate system by fusing the obtained plant point cloud data with the attitude sensor measurement angle, and divides the region of interest according to the radar scanning angle and the field crop planting pattern. The outlier and interference noise in the point cloud data are eliminated by the combined filtering method of straight-through filtering and median filtering. Based on the K-means & improved alpha-shapes algorithm, the accurate acquisition of the height of the boom relative to the top of the crop canopy is realized. In September 2023, a height detection accuracy test was carried out at the Zhangjiakou Potato Experimental Base in Hebei Province. The test showed that the minimum relative error of the detection system based on the k-means & improved alpha-shapes algorithm was 2.65 %, the maximum relative error was 7.67 %, and the average relative error was 4.24 %. The detection results were more accurate and met the job requirements. The system can be used for the accurate detection of the distance between the sprayer boom and the crop, and provides technical support for the accurate spraying operation of the sprayer.

Key word: *Boom sprayer；LiDAR；detection system ; detection algorithm*

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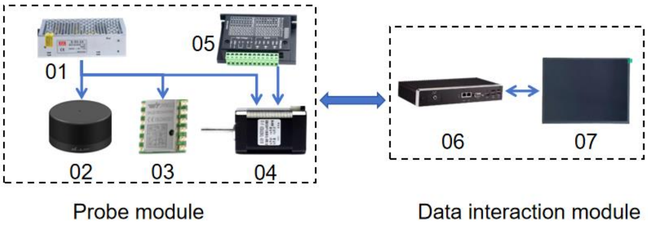
I.Introduction

With the rapid development of agricultural plant protection machinery in the world, large-scale boom sprayers are gradually popularized and applied to the application of crops in the field. The existing boom sprayers have the characteristics of large width (12~42m) and large application amount [1-3]. However, when the sprayer is working in the field, there are problems such as the vibration of the spray rod caused by the large width and the change of the relative height of the spray rod to the crop caused by the uneven working terrain, which often leads to the failure of the sprayer spray rod to maintain the optimal application state, resulting in re-spraying, missed spraying and uneven deposition of the liquid [4-5]. Therefore, In order to improve the height control accuracy of the boom and improve the utilization rate of the liquid, it is very important to detect the height of the boom relative to the crop canopy in real time [6-8]. To this end, this paper uses a low-cost two-dimensional laser radar [9], and designs a set of laser radar-based sprayer boom relative crop canopy height detection system. The field crop canopy is scanned by laser radar detection technology and fusion attitude sensor. At the same time, a distance algorithm between the boom and the top of the crop canopy based on K-means & improved alpha-shapes is proposed, which realizes the accurate detection of the height information of the boom relative to the top of the crop canopy and verifies the detection system through the detection accuracy test.

II.Materials and Methods

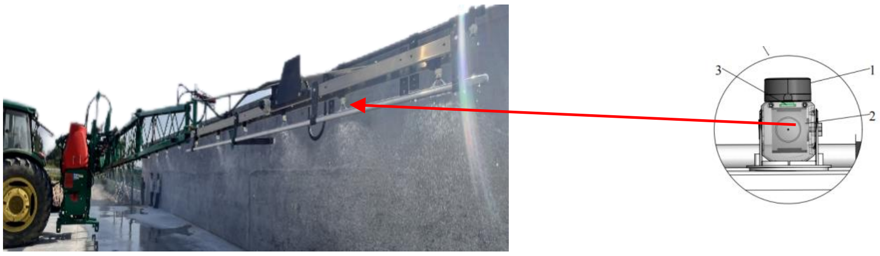
System composition

In order to accurately obtain the phenotypic information of crop canopy in the field, this paper uses two-dimensional laser radar as a ranging sensor. The distance detection system of sprayer boom relative to crop canopy is mainly composed of microcomputer, touch screen, two-dimensional laser radar, attitude sensor, stepper motor and so on. The hardware connection of the device is shown in Figure 1a. The detection module uses the laser radar as the main ranging sensor. The attitude sensor, the stepper motor and the laser radar are integrated in the same device to assist in the distance measurement. The detection module is installed on both sides of the sprayer. The middle section of the end boom square tube, and the laser radar scanning plane is perpendicular to the ground. As shown in Figure 1b, the detection system can be installed on different types of boom sprayers. According to the boom width of the sprayer, the optimal installation position of the detection device can be determined. In this paper, the 3WP-1500 boom sprayer produced by Hessen Tiancheng is used as the carrying platform. The boom width of the sprayer is 24 m, and it is equipped with a boom hydraulic lifting adjustment mechanism, which is suitable for the application of wheat, potato and other crops. After comprehensive investigation, the potato spray operation environment is more complex, and the crop traits have high requirements for the detection method, so this paper selects the potato crop as the research object.



(a)Hardware connection diagram of the device

1. Power supply 2. lidar 3. attitude sensor 4. Stepper motor 5. motor driver 6. Microcomputer 7. Touch screen



(b) Installation schematic diagram of the device

1. Lidar 2. Attitude sensor 3. Stepper motor

Figure 1 System scenario

The two-dimensional laser radar selected in this paper is based on the principle of TOF ranging [10]. The potato plant canopy is scanned in real time by line scanning, and the crop canopy point cloud data obtained by the laser radar is sent to the microcomputer through the serial port. The attitude sensor transmits the detected inclination angle of the boom end to the computer in real time through the UART serial port to compensate the coordinate change of the point cloud data caused by the change of the scanning angle. The microcomputer is equipped with the Windows platform, and the detection system program is written and the data processing algorithm is run by using the Python programming language through the Pycharm platform. The user data visualization interface is built by pyqt5 to monitor the data of the spray rod inclination angle and the distance between the spray rod and the crop canopy obtained by the detection system in real time. The data transmission process is shown in Fig.2.

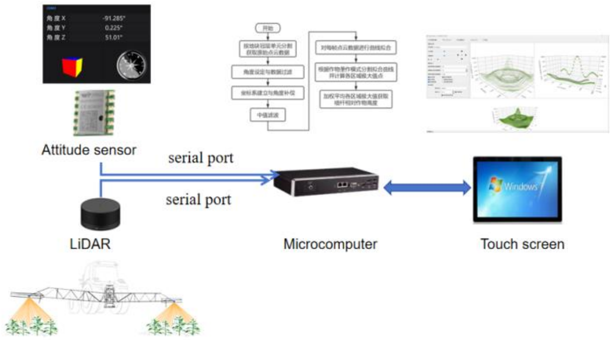


Figure 2 System composition

Sensor selection

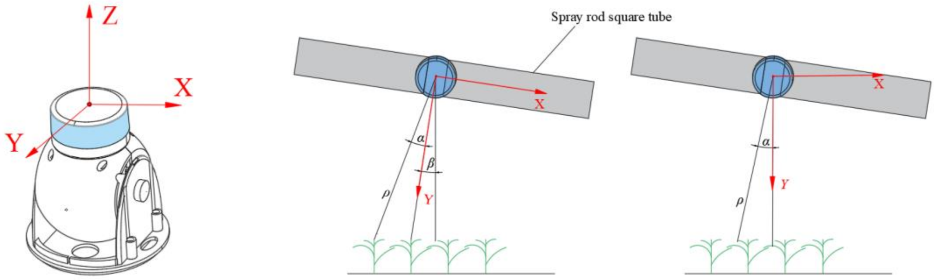
The spraying environment of the sprayer in the potato field planted in the field is complex and the light is strong. Therefore, the laser radar with strong anti-interference ability and suitable for outdoor operation is selected in this paper. At the same time, there are areas with uneven growth in potato field plots. In order to accurately scan the phenotypic profile of potato plant canopy and obtain accurate information of the distance between the spray rod and the crop canopy, a laser radar with high angular resolution and sampling rate is selected to improve the scanning accuracy. In summary, this paper selects a low-cost two-dimensional laser radar (M10P, radium god intelligence, China), the main parameters are shown in table 1.

Table 1 Main parameters of M10P LiDAR

Main parameter	Qualification
Laser band/nm	905
Scan Angle/°	360
angular resolution/°	0.22
Sampling frequency/point s^{-1}	20000
scan frequency /Hz	12
Output data resolution/mm	1
Measured radius/m	100
CI	Network port, standard serial port

During the field operation of the sprayer, due to the change of the terrain in the spraying area and the small excitation of the ground, the boom will vibrate and cause the change of the laser radar attitude. Therefore, the JY901 S attitude sensor is selected in this paper to measure the radar scanning attitude in real time to compensate the coordinate change of the point cloud data caused by the change of the radar attitude, and at the same time to obtain the lateral inclination of the boom.

Point cloud data coordinate system conversion



(a) Sensor Cartesian coordinate system **（b）Point cloud data dynamic angle compensation**

Figure 3 LiDAR point cloud coordinate system and data angle compensation

When the sprayer is working in the field, the laser radar emits a ranging laser in a linear scanning manner to scan the canopy phenotypic profile of the crop to be sprayed under the spray bar in real time, and obtain the distance information of the laser radar scanning center relative to the detected crop and the angle information of the ranging laser. The obtained canopy point cloud data uses a polar coordinate system with the laser ranging laser emission center as the origin. In order to obtain more intuitive information data of the distance between the boom and the crop canopy, it is necessary to convert the polar coordinate system into a two-dimensional rectangular coordinate system.

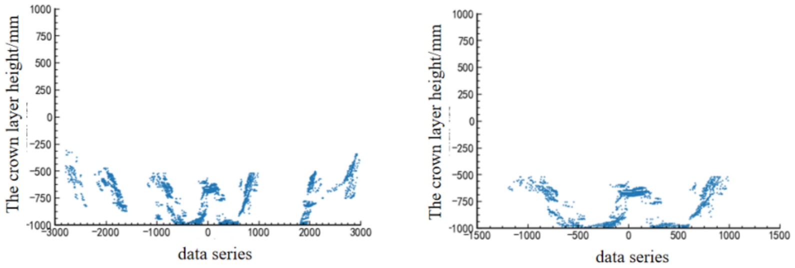
As shown in Figure 3a, the attitude sensor and the laser radar share the Cartesian coordinate system, where the X-axis data of the attitude sensor represents the inclination angle of the boom and the heading angle of the laser radar β, and the Y-axis data represents the elevation angle of the laser radar scanning plane φ. In the process of operation, due to the error between the heading angle of the radar and the pitch angle during installation, the accuracy of data acquisition will be reduced. Therefore, in this study, the initial pitch angle of the lidar is adjusted to 90 ° perpendicular to the ground by the stepper motor. The X-axis angle data of the attitude sensor is used to compensate the heading angle of the lidar, and the output angle range of the radar data is set in real time, so that the Y-axis of the lidar point cloud data coordinate system is perpendicular to the ground in real time, as shown in Figure 3b. Finally, the point cloud data in the lidar polar coordinate system is converted into a rectangular coordinate point cloud coordinate system, and the optimized and simplified point cloud coordinates are

$$\begin{bmatrix}x\\y\end{bmatrix} = \begin{bmatrix}\rho sin_{\varphi}\\ \rho cos_{\varphi}\end{bmatrix} \qquad (1)$$

Detection algorithm of distance between spray boom and crop canopy

Determine the ROI region

The output angle range of the lidar used in this paper is 360°, and it is found in the actual measurement, as shown in Fig. 4a, when the lidar scanning angle is 180° to cover the whole row of ground plants in the field, the canopy point cloud data obtained can only represent the phenotypic contour of the canopy of the three ridges, and the canopy point cloud data in the other scanned areas are discrete and discontinuous



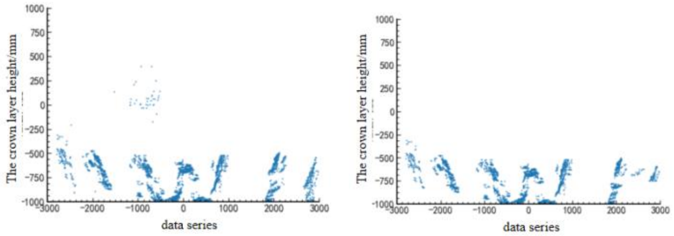
（a）Not divided （b）After the division

Figure 4 Comparison of point cloud data before and after dividing the angle of interest area

In order to filter the redundant point cloud data and improve the accuracy of the data, the potato planting ridge width of the experimental plot is 800mm, plant spacing 250mm, sprayer boom optimal spraying height 400~600mm and other working parameters, the angle of the lidar area of interest is set to [-63°, 63°], and the output angle range of the lidar is [-63°±β, 63°±β]. At the same time, all the frame point cloud data obtained by the lidar scan within the haplo-distance length of the sprayer are taken as the objects processed by the algorithm. Figure 4 shows the multi-frame canopy phenotype profile point cloud data plot after coordinate transformation by the Python-matplotlib tool.

point cloud filtering

In the spray operation of the sprayer, the field environment is complex, and a large amount of dust in the air and the atomized liquid sprayed by the nozzle will drift, resulting in a large amount of interference noise within the range of the laser radar scanning angle, resulting in many outliers in the point cloud data. In order to improve the accuracy of obtaining distance information, it is necessary to perform point cloud filtering and denoising on these outliers and interference points. For some outlier interference points, median filtering is often used for processing. However, in actual acquisition, there are dense outliers far away from the canopy point cloud data. These noise points are manifested as water mist and dust. When median filtering is performed, these dense outliers are mistaken for normal canopy point clouds and cannot be filtered. Therefore, the direct filtering is introduced before the median filtering processing of the data, and the point cloud filtering processing is carried out by means of combined filtering. Based on the potato plant height of the test plot is between 500-700mm, the direct filtering range of this paper is 0-700mm, the median filtering window is 5, and Fig.5 is the point cloud filtering comparison diagram. From Figure 5, it can be seen that the combined point cloud filtering method has better effect. Through the combined filtering, most of the outlier interference noise points can be eliminated, and the point cloud data is smoother.



（a）Filter front （b）After combined filtering

Figure 5 Comparison of point cloud data after median filtering and combined filtering

Acquisition algorithm of boom relative canopy distance based on K-means and improved Alpha-shapes

In the study of the distance information between the spray rod and the top of the crop canopy, the most important process is to segment the single ridge crop point cloud data of the target area and extract the distance information of each region after segmentation. Therefore, this paper uses the k-means algorithm to classify the obtained unlabeled point cloud data set to ensure that the point cloud data containing several canopy top information is divided into several regions, and then the Alpha shapes algorithm is used to fit the edge of the single ridge canopy point cloud data. Finally, the height of the spray rod relative to the single ridge crop is the vertex of the edge fitting line. K-means is a commonly used clustering algorithm. The main process of the algorithm is as follows :

1) According to the characteristics of the point cloud data of the target area obtained by the import, the required number of clusters K is determined ; 2) K points are randomly selected from the point cloud data as the initial clustering center. 3) Calculate the Euclidean distance from each point to each cluster center, and assign the points to the cluster nearest to the corresponding cluster center one by one. 4) After all points in the point cloud data are assigned, for each cluster, recalculate its cluster center (that is, the center of mass of all points in the cluster 5) Repeat steps 3), 4), until the required number of iterations is met or the cluster center is no longer changed. The Euclidean distance d between the point cloud data and the cluster center is :

$$d(x, K_i) = \sqrt{\sum_{j=1}^{m}(x_j - K_{ij})^2} \qquad (2)$$

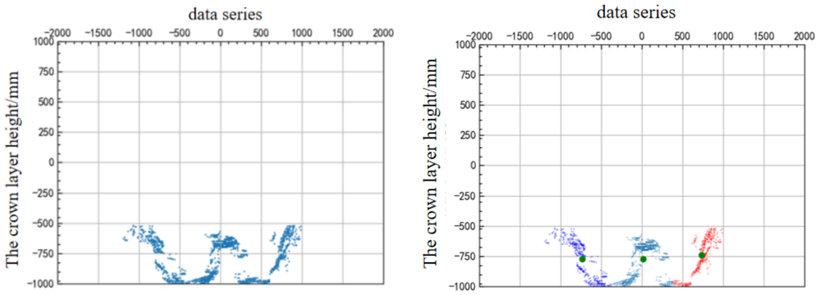
Here, x is the point in the point cloud data, Ki is the i th cluster center, and m is the dimension of the data object (m = 2).

The goal of clustering is to minimize the sum of squared errors of the Euclidean distance between each point in the point cloud data set and its nearest cluster center. The sum of squared errors of the entire point cloud data set is SSE :Where k is the number of clusters.

$$SSE = \sum_{i=1}^{k} \sum_{x \in K_i} |d(x, K_i)|^2 \qquad (3)$$

Where k is the number of clusters.

In this paper, according to the characteristics of the point cloud data of the three ridges, K = 3 is taken to cluster the point cloud data after two-dimensional spatial filtering. Finally, the point cloud data is clustered into three regions containing only single ridge canopy data information. The clustering results are shown in Figure 6. After k-means clustering, the point cloud data set containing the canopy of 3 ridge plants is divided into three categories, and each category contains the point cloud information of the canopy of single ridge plants. Data sequence spray boom relative canopy height



（a）Filtered raw point cloud **（b）k-means clustering**

Fig.6 Comparison of point cloud data before and after k-means clustering

In order to obtain the accurate information of the distance between the spray rod and the top of the potato plant canopy, it is also necessary to obtain the distance between the clustered spray rod and the single ridge plant canopy. Therefore, based on the improved Alpha-shapes (A-shapes) edge fitting algorithm, the effective point cloud phenotypic contour points of the single ridge canopy are obtained by edge fitting, and the height of the edge vertex of the fitted canopy point cloud data is used as the distance between the spray rod and the top of the plant canopy.

In this paper, in the python environment, under the parameter of r value of 25, the a-shapes algorithm is used to fit the edge line of the clustered point cloud data. According to the test results shown in Fig.7, it can be seen that the edge contour of point cloud data containing the distance information between the boom and the top of the canopy can be fitted by the conventional a-shapes algorithm, and the fitted edge line can converge to the point cloud data, but the fitted edge line still has prominent outliers, which affects the accuracy of data acquisition.

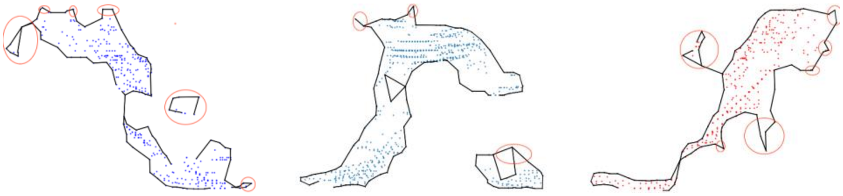


Fig.7 Edge fitting effect of alpha-shapes algorithm

In this paper, an outlier removal algorithm is introduced based on the original fitting algorithm. The algorithm flow is as follows :

(1) Establish two-dimensional grid. According to the number of point cloud data samples after clustering and the range of horizontal and vertical coordinates, a two-dimensional mesh of appropriate size is established. Refer to the point cloud grid size calculation method proposed in the relevant literature, set the grid side length l as

$$l = t \times \sqrt{(X_{max} - X_{min}) \times (Y_{max} - Y_{min})/m} \qquad (4)$$

Where t is the adjustment coefficient, the value range is [1,1.5] ; xmax and Ymax are the maximum values of the horizontal and vertical coordinates of the point cloud data in this area ; xmin and Ymin are the minimum horizontal and vertical coordinates of point cloud data in this area ; m is the number of sample points in the point cloud data set.

(2) Grid labeling and outlier elimination. As shown in Figure 8, the grid without point cloud data is marked as an empty grid, the grid with point cloud data is marked as an effective grid, and the grid with edge lines after edge fitting is marked as an edge grid. Neighborhood detection is performed on the effective grid. If the 8 neighborhoods of the effective grid contain point cloud data, they are marked as internal grids. If the number of internal grids in the neighborhood of the edge grid is less than 2, it is determined as the outlier grid, and the outlier grid is eliminated.

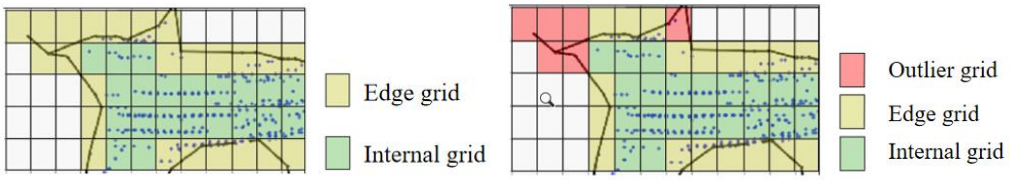


Fig.8. Grid markers and outlier removal

Therefore, the edge fitting effect of the alpha-shapes algorithm is improved by eliminating the outliers. The improved algorithm fitting result is shown in Figure 9. It can be seen that the edge fitting accuracy of the canopy point cloud data is improved by eliminating the outliers of the edge line through gridding. The fitted edge can better express the phenotypic contour at the top of the canopy. The maximum value of the canopy edge vertex in each region is the distance between the spray rod and the top of the single ridge crop canopy. Finally, the distance between the spray rod and the top of the crop canopy in this region is the average value of the maximum value of the canopy edge vertex in each region. The calculation formula of Hrelative-canopy relative to the crop canopy height in this area is as follows.

$$H_{\mathrm{relative-canopy}} = \frac{\sum_{i=1}^{n} H_i^{max}}{n} \tag{5}$$

Among them, H_i^{max} is the maximum value at the top of the canopy in the relative area of the boom, and n is the number of clusters (n takes 3).

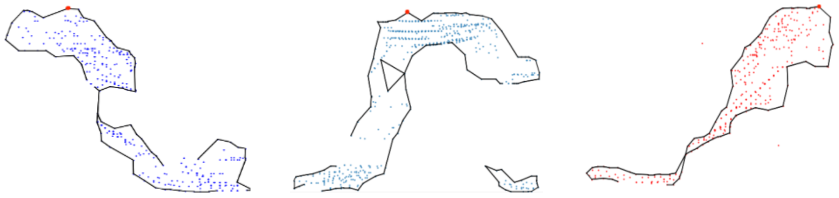


Fig.9 Edge fitting results based on the improved alpha-shapes algorithm

III. Performance verification test and result analysis

In order to verify the applicability of the detection system and the accuracy of the detection method, the detection system was loaded on the 3WP-1200 wide boom sprayer produced by Xisen Tiancheng.In September 2023, the detection accuracy test of the boom relative crop canopy height detection system was carried out in the potato test base of Zhangjiakou, Hebei Province. The test machine is used in the test scene as shown in Fig.13.During the test, the spray system is turned on and water is used instead of liquid medicine.

(a) Equipment Installation **(b) Test equipment** **（c) Test scenarios**

Fig.10 Schematic diagram of test equipment and test scene

Test materials and methods

Main experimental materials : Wide spray boom sprayer based on laser radar detection system, tape (minimum scale of 1mm), level.

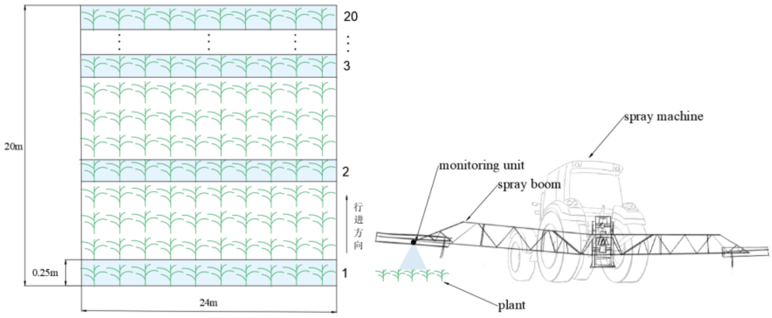


Fig.11 Schematic diagram of detection accuracy test

Test content and method : The accuracy of the lidar detection system supported by different algorithms was explored by scanning and sampling the potato plant plots in the field. The experiment is as shown in Figure 11. A 20×24m flat potato field plot was selected. The potato in the experimental field was planted in a single ridge and single row mode. The ridge width was 800 mm, the plant height was 400-600 mm, and the plant spacing was 250 mm. In the test, only the left spray rod was installed with the detection device. Before the test, the laser radar scanning plane in the detection device was set perpendicular to the ground by the attitude sensor, and the height of the spray rod from the ground was set to 1 m, as shown in Fig. 14. The detection device was turned on every 1 m laser radar for sampling during the test. During the test, the height of the spray rod was not adjusted, and a total of 20 point cloud data samples of crop plants were finally obtained. At the same time, the distance between the spray rod and the top height of the crop canopy in the No.1-20 sampling area was manually measured by tape, and 20 data control samples were obtained according to the calculation of formula (3).

Analysis of test results

Analysis of detection accuracy test results : By running different algorithms on the point cloud data samples obtained from the test, the corresponding distance information between the sprayer boom and the top of the potato plant canopy was obtained. The system measurement results and manual measurement results are shown in Table 1. It can be seen from Table 1 that the maximum relative error of the distance between the sprayer boom and the top of the canopy based on the KIMA algorithm is 7.47 %, the minimum relative error is 2.65%, and the average relative error is 4.24%. It can be seen that the detection method of the distance between the spray rod and the top of the crop canopy based on KIMA has high accuracy and meets the operation requirements.

Table 2 Comparison of the distance between the relative canopy top of the boom obtained by different algorithms and the manual measurement results

Sample No.	Polynomial fitting results/mm	KIMA results/mm	Manually measure results/mm	Polynomial fitting error/%	KIMA error/%
1	473.26	531.76	513	7.75	3.66
2	439.59	454.38	467	5.87	2.70
3	464.31	491.43	471	1.42	4.34
4	519.45	470.17	483	7.55	2.66
5	438.03	497.34	476	7.98	4.48
6	437.81	468.12	481	8.98	2.68
7	431.67	451.78	478	9.69	5.49
8	537.48	460.23	487	10.37	5.50
9	442.40	469.31	497	10.99	5.57
10	397.62	448.21	431	7.74	3.99
11	500.43	513.19	534	6.29	3.90
12	489.97	503.91	521	5.96	3.28
13	499.92	504.29	545	8.27	7.47
14	475.54	493.73	519	8.37	4.87
15	486.90	479.10	507	3.96	5.50
16	467.87	489.12	514	8.97	4.84
17	447.79	500.32	487	8.05	2.74
18	467.56	510.93	488	4.19	2.65
19	465.19	481.49	506	8.07	4.84
20	450.53	520.21	502	10.25	3.63

IV. Conclusion

(1) The designed detection system of the height of the spray boom relative to the top of the crop canopy meets the design needs, and can realize the accurate detection of the canopy height of the spray boom relative to the crop to be sprayed during the field operation of the sprayer, which provides technical support for the intelligent and accurate operation of the sprayer.

(2) By designing a detection system based on two-dimensional laser radar, and proposing an algorithm based on k-means & improved alpha-shapes to obtain the height of the spray rod relative to the top of the crop canopy. Through the detection accuracy test, the average relative error of the detection system is 4.24 %. It meets the operation requirements of high-precision boom relative crop canopy height detection.

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