2024 39th Youth Academic Annual Conference of Chinese Association of Automation (YAC) | 979-8-3503-7922-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/YAC63405.2024.10598559

Research on the volume measurement algorithm and application of irregular objects based on 3D point cloud

1st Weitong Yu
Department of electrical engineering
Anhui Polytechnic University
Wuhu, China
17754838796@163.com

2nd Fanyong Cheng
Department of electrical engineering
Anhui Polytechnic University
Wuhu, China
chengfanyong@ahpu.edu.cn

3rd Mingyan Zhan
Department of electrical engineering
Anhui Polytechnic University
Wuhu, China
mingyanhappy0912@163.com

Abstract*—In recent years, with the development of 3D laser scanning technology, it has provided the basis for the wide application of irregular object volume measurement based on point cloud. However, in practice, how to measure the volume of irregular objects in a single viewing Angle, the existing methods still have some limitations, such as overfitting the surface of the point cloud, large measurement error of non-convex objects, and non-closed point cloud can not be measured. In this paper, a method of measuring the volume of irregular objects in single view based on 3D point cloud is proposed. Firstly, an infrared camera is used to capture the point cloud image of the object at the overlooking Angle, and the spatial position correction is carried out on the point cloud image to make the carrying object plane coincide with the XOY plane. Secondly, the point cloud data unrelated to the measured object is removed, and the object point cloud is projected vertically down to the XOY plane, and the projected area of the point cloud is calculated using regression model and grid method. Finally, the measured object is regarded as a combination of multiple columns with the same base area, and the exact volume of the object is calculated by the accumulation method. Experimental results show that the volume measurement of irregular objects can be completed by using the method proposed in this paper under a single view Angle, and the average relative error rate is only 3.52%.

Keywords*—3D point cloud; Single view Angle; Irregular objects; Regression model; Grid method; Volume measurement.

I. INTRODUCTION

Volume is an important parameter in the shape analysis of space objects, and volume calculation involves two types of regular geometry and irregular geometry [1]. The volume of regular body can be accurately measured by using the existing calculation formula. On the contrary, how to measure the volume of irregular object has always been a difficult problem, mainly due to the different shapes of irregular objects, there is no ready-made and universal calculation formula and method. With the development of 3D laser scanning technology [2], the use of point cloud to display object models has received a lot of theoretical research and practical application [3]. 3D laser scanning technology, also known as reality reproduction technology [4], has the advantages of high precision, high resolution and strong applicability. It can quickly and accurately obtain the 3D spatial information of the measured object [5], providing a new model for the volume measurement of irregular objects [6], and is widely used in various fields such as agriculture, medical treatment, ship transportation [7] and geographical survey.

In practical applications, the types of objects to be measured are complex and the environments to be measured are diverse, so it is necessary to propose a method to measure the volume of irregular objects based on 3D point cloud in a single viewing Angle. The existing methods for measuring the volume of irregular objects based on 3D point cloud are basically divided into the following four categories: convex hull algorithm [8,9,10], slice method [11,12], surface reconstruction algorithm [13,14,15], and triangulation method [16,17,18]. The convex hull algorithm is only suitable for convex objects, and the measurement error is larger for non-convex objects. The surface reconstruction algorithm is affected by the point cloud density, accuracy and the number of generated grids, and the measurement effect of non-convex objects is not ideal, and surface overfitting is easy to occur. The slicing method is only applicable to closed point clouds. Triangulation method needs to fit the point cloud into a surface model. When facing complex point clouds or non-convex point clouds, point cloud triangulation is prone to overfitting. The point cloud data obtained in single view is not closed, complex and non-convex, and the existing methods are not applicable.

This paper commences with the conventional grid method and supplements it with a regression model to precisely compute the projected area of the point cloud. Subsequently, it achieves high-precision measurement of irregular object volumes through the accumulation method principle. Depth perception cameras are employed to capture point cloud data from an overhead perspective, while the combination of the regression model and grid method measures the point cloud's projection area. This approach addresses issues encountered by the traditional grid method, such as accurately defining mesh side lengths and mitigating the influence of peripheral grid contours on projection area measurements. As a result, the volume accuracy attained through the accumulation method is enhanced, presenting promising prospects for industrial applications.

II. SYSTEM DESCRIPTION

A. Measure System

In the study of the volume measurement algorithm of single-view irregular objects, a high-precision depth-sensing camera is used as a measuring element to scan the object [19] to obtain the object's overhead point cloud. During the measurement, the camera is located at the overlooking Angle, and the infrared dot matrix laser in the arranged position is illuminated to the surface of the irregular object. The infrared

Fund Projects: Supported by Key Research and Development Project of Wuhu City (2022yf42), Special Fund for Collaborative Innovation of Jiujiang District of Anhui Engineering University (2022cyxtb10), Open Research Fund of Key Laboratory of Detection Technology and Energy Saving Device of Anhui Province (JCKJ2021B06).

camera of the camera is used to receive the distorted infrared dot matrix on the surface of the object, and the three-dimensional point cloud data of the surface of the object is obtained through the change of the distance and size of the point interval. The measurement principle of depth-sensing camera is shown in Figure 1.

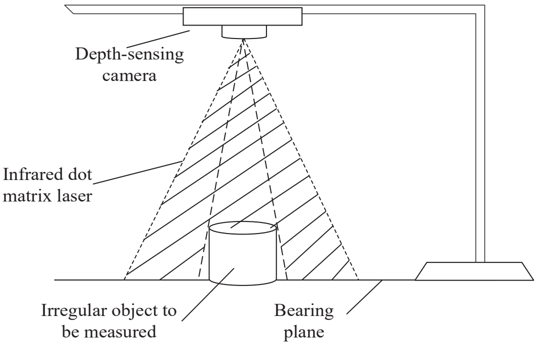


Fig.1. Measurement principle of depth-sensing camera.

B. Measure Process

FIG. 2 is a flow chart for measuring the volume of irregular objects in this paper. When the initial point cloud data is visualized, the three-dimensional spatial coordinate system is built with the camera as the center, so the obtained point cloud data is reversed after visualization. In order to facilitate various subsequent processing of the point cloud, the spatial position of the point cloud needs to be corrected. By fitting the plane model of the placed object and making it coincide with the XOY plane through rotation and translation transformation, the three-dimensional coordinate system with the Z axis up and perpendicular to the placed plane can be obtained. Then, plane segmentation, outlier removal and clipping of point cloud are carried out to remove the influence of irrelevant point cloud on measurement. Finally, the point cloud is projected down to the XOY plane, and the projected area is measured using the optimized mesh method, and then the volume of the irregular object is obtained.

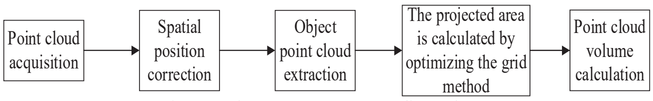


Fig.2. Volume measurement flow chart.

III. Basic Principle

A. 3D Point Cloud Spatial Position Correction

In three-dimensional space, any plane can be obtained by rotation and translation of the other plane. In order to make the plane point cloud of the measured object coincide with the XOY plane, the corresponding rotation matrix and translation matrix need to be obtained. If the two planes are parallel, the rotation matrix is the third-order unit matrix. If they are not parallel, the two planes must have a line of intersection. With the line of intersection as the rotation axis, the plane parallel can be realized by calculating the rotation Angle, and then the average height of the plane model can be translated to realize the plane coincidence. The method of spatial position correction is derived as follows:

The random sampling consistency algorithm RANSAC[20] was used to fit the plane model of the placed object. Set the number of iterations and threshold, randomly select a part of the data points as the inner point set, and use these data points to fit the plane model. For the remaining data points, calculate their distance to the fitted plane model. If the distance is less than the threshold, it is added to the inner point collection. The above process is repeated and the model with the maximum number of interior points is selected as the final fitting result.

Get the normal vector of the plane model. Using the cross product operation of vectors to compute a normal vector of the plane, the result is a new vector that is perpendicular to both vectors taking the cross product. Take three points on the plane that are not collinear, P1(x1,y1,z1), P2(x2,y2,z2), and P3(x3,y3,z3). The three non-collinear points are chosen to ensure that the vectors P1P2 and P1P3 are not collinear or parallel, only in this case the cross product of the vector is a non-zero vector, that is, the normal vector N of the plane. The formula is as follows:

$$\begin{cases} P_1P_2 = P_2 - P_1; \\ P_1P_3 = P_3 - P_1; \\ N = P_1P_2 \times P_1P_3 = (a, b, c). \end{cases} \tag{1}$$

If the third component c of N is close to zero, the fitting plane model is considered parallel to the XOY plane, and the rotation matrix is the identity matrix. If c is not close to zero, the desired rotation matrix is computed based on the normal vector.

Construct the vector V=(b,-a,0) perpendicular to the normal vector and parallel to the plane XOY, using the vector V as the rotation axis of the plane. If the plane is rotated counterclockwise by default, the rotation Angle is the Angle between the normal vector N and the unit vector A(0,0,1). The cosine value of the rotation Angle is obtained by using the dot product formula of the vector, as shown in equation (2) :

$$\cos\theta = (A \cdot N) / (|A| \times |N|) \tag{2}$$

Construct the antisymmetric matrix Vx of vector V and derive it by cross product between vectors. The derivation formula is as follows:

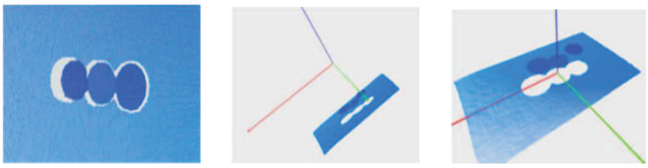
$$V=\begin{bmatrix} b \\ -a \\ 0 \end{bmatrix}, \beta=\begin{bmatrix} l \\ m \\ n \end{bmatrix}, V\otimes\beta=\begin{bmatrix} -an \\ -bn \\ bm+al \end{bmatrix}=\begin{bmatrix} 0 & 0 & -a \\ 0 & 0 & -b \\ a & b & 0 \end{bmatrix}\begin{bmatrix} l \\ m \\ n \end{bmatrix},$$

$$V_X=\begin{bmatrix} 0 & -V[2] & V[1] \\ V[2] & 0 & -V[0] \\ -V[1] & V[0] & 0 \end{bmatrix}=\begin{bmatrix} 0 & 0 & -a \\ 0 & 0 & -b \\ a & b & 0 \end{bmatrix} \tag{3}$$

Use the Rodriguez rotation formula [21] to find the rotation matrix. The Rodriguez rotation formula is a mathematical tool for rotating vectors in three dimensions. It is based on the concept of linear algebra and realizes the rotation of vectors by matrix multiplication. The Rodriguez rotation matrix can be expressed as:

$$H = I + \sin\theta * V_X + (1-\cos\theta) * V_X^2 \tag{4}$$

Where H is the rotation matrix, I is the identity matrix, θ is the Angle of rotation, and Vx is the antisymmetric matrix of the rotation axis. H represents the rotation matrix of any vector in three-dimensional space with a counterclockwise theta Angle around the rotation axis V vector. After the point cloud is rotated by the rotation matrix H, the point cloud model of the object bearing plane is parallel to the XOY plane. The fitted plane model point cloud is divided, the height mean e of all points in the plane model point cloud is calculated, and the plane model is overlapped with the XOY plane by constructing the translation vector (0,0, -e) translation point cloud. The process of spatial position correction is shown in Figure 3.



(a) (b) (c)

Fig.3. Process of spatial position correction. (a) Shoot point cloud visualization, (b) coordinate system visualization, (c) point cloud image after space correction.

B. Object Point Cloud Extraction

In the process of acquiring three-dimensional point clouds of the measured object, due to the influence of the infrared dot matrix density of the depth-sensing camera, the placement plane of the measured object, the surrounding environment and other factors, there are some interference points that do not belong to the measured object in the original point cloud data obtained. In order to ensure the subsequent measurement accuracy, these irrelevant point clouds need to be removed. The following two methods are mainly adopted:

*1)*Remove the point cloud data of the object carrying plane. The random sampling consistency algorithm (RANSAC) is used to fit the plane model of the point cloud plane after spatial position correction. The algorithm randomly selects a part of sampling points each time to estimate the parameters of the plane model, and then evaluates the reliability of the model according to the number of points within the threshold range of the plane model distance. The optimal fitting result is obtained by setting the maximum number of iterations, and finally the point cloud data corresponding to the fitted plane model is removed.

*2)*Create axial alignment bounding boxes to limit the range of point cloud data. When processing raw point cloud data, it is common to encounter interference points caused by the edge part of the carrying plane, which may be higher than the plane. Even by removing the fitted plane model, the problem of these interference points cannot be effectively solved. Therefore, axial alignment bounding boxes are introduced as a means of limiting the range of point cloud data. The axial alignment bounding box is a cuboid parallel to the axis that can fully contain the given point cloud data. By setting the corresponding parameters, we can get a rectangular bounding box surrounding the point cloud data and remove the irrelevant point cloud data.

C. The Projected Area is Calculated by Optimizing the Grid Method

The original three-dimensional point cloud data of the measured irregular object is obtained from the overlooking Angle, and each point in the point cloud is regarded as one of the countless columns composed of the measured irregular object, that is, each point corresponds to a column. Therefore, the base area of the object needs to be measured to further calculate the volume. The treated point cloud is projected vertically down, and the projected area of the point cloud is approximated by the grid method to represent the bottom area of the measured irregular object. The specific implementation method of point cloud projection is as follows: import the 3D point cloud information of the measured object, obtain X and Y coordinates from the point cloud data, create an all-zero number group with the same size as the X array as the Z coordinate, stack the X, Y and Z coordinates according to the column direction, and create a new two-dimensional array, where each column corresponds to the value of a coordinate axis. In this way, a two-dimensional array containing point cloud data is obtained, and each row corresponds to the three-dimensional spatial coordinates of a point in the point cloud to achieve the projection of the point cloud on the XOY plane.

The existing Grid Method [23,24] calculates the projected area of the point cloud by projecting the point cloud onto a two-dimensional grid with a set size and counting the number of grids containing projection points. The grid effect diagram is shown in Figure 4. The defect of this measurement method is that it cannot accurately set the appropriate small grid size and resolution, and the calculated projection area is often larger than the real value due to the influence of the peripheral contour grid of the projection point cloud. In this paper, the regression model is used to predict the optimal mesh side length and achieve accurate calculation of the projected point cloud area. The main steps are as follows:

1) Constructing a dataset involves following the grid method principle for calculating projected areas. Inputs comprise the length and width of the smallest rectangle encompassing the projected point cloud, along with the mean distance of all points within the projected cloud. The output represents the small grid's side length meeting the paper's measurement accuracy criteria. Sequential numbering is assigned to 120 processed point clouds projected onto the XOY plane, with inputs and outputs computed accordingly. The maximum and minimum X and Y axis values in the projected point cloud determine the enclosing rectangle, from which its dimensions are derived. Each point in the projected cloud is traversed to compute its nearest point distance, yielding the mean point distance. Manual measurement determines the actual projected area of the object, guiding continual adjustment of small grid parameters to approximate the measured area to the real value, with an accuracy requirement of 10-6m. Ten randomly chosen groups form the test set, while the remaining 110 groups constitute the training set.

2) Predicting the size of the small grid: the data used as the training set is imported into the regression model [25] for learning, and the side length of the small grid corresponding to the test set data is predicted.

3) Construct a rectangular box containing a projection point cloud. The four edges of the rectangle box are required to be separated by a small grid side length from the X-axis maximum and minimum coordinate points and Y-axis maximum and minimum coordinate points of the projection point cloud.

4) Create a grid: According to the small grid size predicted by the model, create a grid in a two-dimensional space.

5) Projection point cloud to grid: All points in the point cloud are projected vertically and downward onto the set grid. The X and Y coordinates in the point cloud are used to determine the location of a point in the grid, and then the grid cell containing that location is marked as covered.

6) Calculate the projected area: Traverse each cell in the grid and calculate the covered area by counting the number of covered cells.

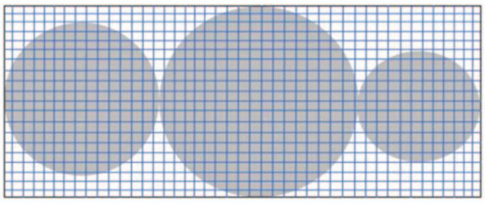


Fig.4. Grid effect diagram.

D. *Point Cloud Volume Calculation*

By counting the number of points in the point cloud model of the irregular object after processing, the measured object is regarded as a combination of columns with the same base area. The base area of the column can be calculated according to the projected area of the irregular object. Each point in the object 3D point cloud corresponds to a cylinder, and the volume is calculated by summing the volume of the cylinder. The calculation formula is as follows:

$$V = \frac{S}{n}\sum_{i=1}^{n} h_i \tag{5}$$

The height of the point hi is equal to the height of the column, the object projection point cloud area S is the sum of the bottom area of each point cloud corresponding to the column, the number of points n of the output object point cloud, the calculated projection area S is divided into n parts, you can get the bottom area of the column S1, the bottom area of the column multiplied by the height of all points of the object and the volume of the object V.

IV. Experimental Verification

A. *Experiment And Analysis*

This experiment uses different combinations of multiple cylinders and cuboids to simulate irregular objects. Before the experiment begins, the object to be measured is manually measured using a vernier caliper to pass the meter

The projected area and true volume of the measured object are obtained.

An Intel D435 camera was used to acquire the 3D point cloud of the object. The camera was connected to the computer and fixed on the triangular bracket, and the object under the camera was placed directly below the camera for shooting. The experimental measurement site was shown in Figure 5.Figure 6 is a visualization of the collection point cloud using Intel Vision software that comes with the camera.

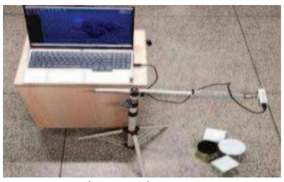
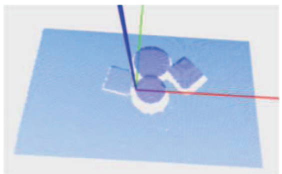


Fig.5. Experimental measurement site. Fig.6 Visualization of collection point cloud.

The experiment obtained 120 groups of 3D point clouds with different combinations and different positions from the overlooking Angle, and numbered these point clouds starting from 01. Each point cloud number corresponds to three input values and one output value. Spatial position correction and plane model removal were performed on 120 sets of 3D point cloud data, as shown in FIG. 7 and 8.



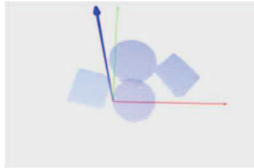


Fig.7. Spatial position correction. Fig.8. Plane model removal.

The point cloud removed from the plane model is projected vertically downwards onto the XOY plane, as shown in Figure 9.

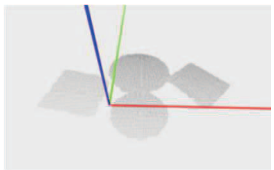


Fig.9. Point cloud projection.

The length and width of the smallest rectangle containing the projection point cloud and the average point distance of the projection point cloud are calculated as the three input values of the corresponding point cloud number in the data set. Adjust the side length parameters of the small and medium grids in the grid method so that the measured projected area gradually approximates the real value (the accuracy of the measured projected area is required to reach 6 decimal places), and the required small grid side length is used as the optimal output value of the corresponding point cloud number.

The collected data set is built, 10 groups of data are randomly selected as the test set, and the remaining 110 groups are trained as the training set for the regression model. The original three-dimensional point cloud of the test set is shown in Figure 10, and the projected point cloud is shown in Figure 11.

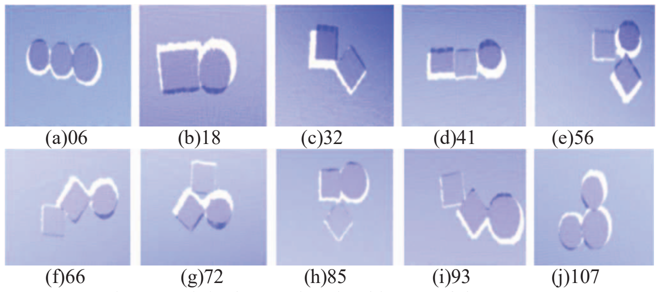


Fig.10. Original 3D point cloud image of the test set.

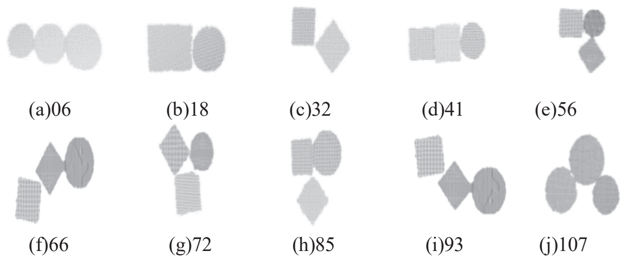


Fig.11 Test set projection point cloud image.

The prediction results of the model for the test set are shown in Table 1. It can be seen from Table 1 that among the ten groups of predicted values, the predicted value No. 66 has the smallest relative error, while the predicted value No. 06, 41 and 107 has a larger relative error, with the maximum relative error of 8.97%, the minimum relative error of 0.2% and the average relative error of 3.60%. The accuracy of the prediction model for small grid side length is better.

TABLE I. Grid side length error

ID	Predicted value/m^2	Optimal value/m^2	Relative error/%
06	0.00186700168	0.0017203122	8.55
18	0.00147495649	0.0015329080	3.38
32	0.00180096266	0.0017788000	1.25
41	0.00183413146	0.0020011890	8.33
56	0.00183735935	0.0018273672	0.60
66	0.00185474272	0.0018520000	0.20
72	0.00188095193	0.0018668000	0.78
85	0.00188888122	0.0018710000	0.96
93	0.00179800347	0.0017490400	2.93
107	0.00177119284	0.0019458000	8.97
Mean value/%			3.60

Using the small grid side length predicted in Table 1, the area occupied by the projected point cloud is calculated and compared with the real value. The results are shown in Table 2. The relative error of No. 66 is the smallest, the relative error of No. 107 is the largest, the minimum relative error is 0, the maximum relative error is 6.59%, and the average relative error is 1.91%. It can be seen that the percentage error of projection area measurement results is small, and accurate projection area measurement is achieved.

TABLE II. PROJECTION AREA PREDICTION

ID	Projected area/m^2	True value/m^2	Relative error/%
06	0.02388398412	0.0230318007	3.70
18	0.01411897321	0.0143895016	1.88
32	0.01447559094	0.0143710000	0.73
41	0.01939704434	0.0200455016	3.23
56	0.02014055598	0.0200455016	0.47
66	0.02004529118	0.0200455016	0
72	0.02011695529	0.0200455016	0.36
85	0.02396183012	0.0238743176	0.37
93	0.02429461587	0.0238743176	1.76
107	0.02151439692	0.0230318007	6.59
Mean value/%			1.91

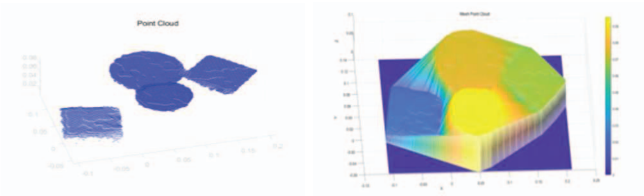
Calculate the height cumulative value of all points after plane model removal and the number of points after point cloud projection. Calculate the volume by using formula (4) through the accumulation method, and compare the measured results with the actual volume. The results are shown in Table 3. The maximum relative error is 6.17%, the minimum relative error is 0.54%, and the average relative error is 3.52%. The error is small, which can meet the accuracy requirements of the volume measurement of irregular objects.

TABLE III. MEASUREMENT VOLUME RESULTS ANALYSIS

ID	Measured volume/m^3	Actual volume/m^3	Relative error/%
06	0.001832206	0.0018510040	1.02
18	0.001121507	0.0011835396	5.24
32	0.000747132	0.0007220215	3.48
41	0.001235442	0.0012820948	3.64
56	0.001221177	0.0012820948	4.75
66	0.001275144	0.0012820948	0.54
72	0.001295542	0.0012820948	1.05
85	0.001426472	0.0015203002	6.17
93	0.001598657	0.0015203002	5.15
107	0.001773584	0.0018510040	4.18
Mean value/%			3.52

B. *Contrast Experiment*

In order to verify the superiority of the proposed method, the surface reconstruction method based on 3D point cloud interpolation fitting was used to measure the volume of ten groups of test set point clouds. The measurement process is shown in Figure 16. The mesh fitting surface was generated by point cloud interpolation and the volume of all grid columns was accumulated to obtain the measurement results.



(a)Look down at the corner clouds (b)Interpolation mesh fitting model

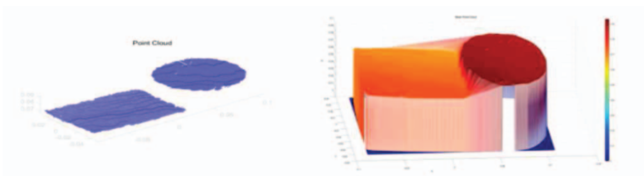
Fig.16. Measurement process

The experimental measurement results are shown in Table 4. Among the ten groups of measurement results, the maximum relative error was 52.60%, the minimum relative error was 0.32%, the average relative error was 23.17%, and the relative error of 8 groups was more than 10%.

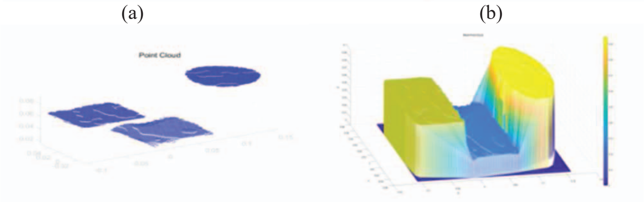
TABLE IV. COMPARISON OF VOLUME MEASUREMENT RESULTS AND RELATIVE ERRORS BY INTERPOLATING AND FITTING SURFACE RECONSTRUCTION METHOD

ID	Measured volume/m^3	Interpolation fitting error/%	Our algorithm error/%
06	0.002075	12.10	1.02
18	0.001230	3.93	5.24
32	0.000936	29.63	3.48
41	0.001278	0.32	3.64
56	0.001528	19.18	4.75
66	0.001813	41.41	0.54
72	0.001662	29.63	1.05
85	0.001685	10.83	6.17
93	0.002320	52.60	5.15
107	0.002445	32.09	4.18
Mean value/%		23.17	3.52

Compared with the algorithm in this paper, only the relative errors of No. 18 and No. 41 among the ten groups of measurement results of the surface reconstruction method with interpolation fitting are slightly lower than those of our algorithm. The two groups of numbered top-down corner cloud images and interpolation meshing fitting models are shown in Figure 17. The relative errors of the other 8 groups are much larger than those of our proposed algorithm, among which the measurement results numbered 66 and 93 are the two groups with the largest relative errors, and the measurement process is shown in Figure 18.

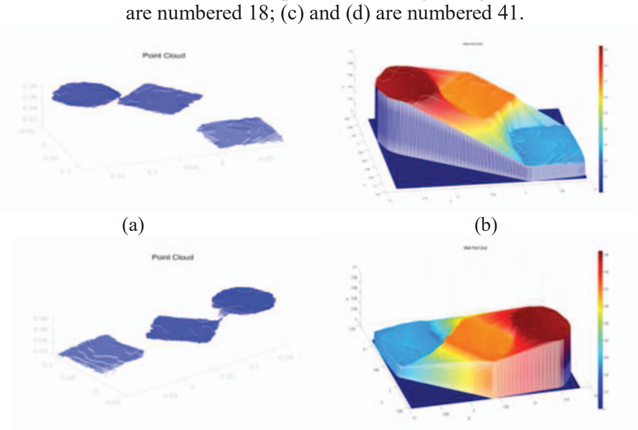


(a) (b)



(c) (d)

Fig.17. Two groups of overhead corner cloud images with minimum relative error and interpolation meshing fitting model. (a) and (b) are numbered 18; (c) and (d) are numbered 41.



(a) (b)

(c) (d)

Fig.18. Two groups of overhead corner cloud images with the largest relative errors and interpolation meshing fitting model. (a) and (b) are numbered 66; (c) and (d) are numbered 93.

Comparing FIG. 17 and FIG. 18, non-convex surfaces are approximated as planes by the interpolation fitting surface reconstruction method during measurement, leading to increased errors with more non-convex surfaces. As the dataset consists of point cloud data captured from a single viewing angle, representing objects with varying heights and numerous non-convex surfaces, measurement accuracy suffers. In this experiment, combining the overhead perspective point cloud with an enhanced grid method better captures the surface characteristics of the object, resulting in improved measurement accuracy.

V. Conclusion

This paper introduces a novel single-view measurement method based on machine vision for assessing the volume of irregular objects. The approach leverages a linear regression model to enhance the conventional grid method. Through the utilization of 3D point cloud acquisition, point cloud spatial correction, and plane removal techniques, the method extracts pertinent point cloud data. Subsequently, an enhanced grid method is devised to accurately measure the volume of irregular objects. Experimental findings demonstrate that:

1) The improved grid method based on linear regression model can accurately measure the projected area of the object point cloud;

2) The measured object is regarded as a collection of multiple columns with the same base area, and each point in the processed object point cloud corresponds to a column. The method of representing the volume of the measured object by measuring the sum of the volume of the column is feasible and accurate.

3) The algorithm in this paper realizes the high-precision measurement of the volume of irregular objects under a single viewing Angle, and has good industrial application value.

References

[1] LI Bin, WEI Junbo, MA Bochao, et al. Three-dimensional laser point cloud slicing method for calculating irregular volume [J]. Journal of Geodesy and Cartography, 2019, 48(1): 42-52.

[2] ZHANG Jixing, CHENG Xiaojun, CHENG Xiaolong. Application of three-dimensional laser scanning technology in ship displacement measurement [J]. Chinese Journal of Lasers, 2016, 43(12): 4003.

[3] HU Yanwei, WANG Jianjun, FAN Yuanyuan, et al. Three-dimensional modeling and volume calculation of space objects based on LiDAR [J]. Chinese Journal of Lasers, 2020, 47(5): 487-488.

[4] MA Daoming, ZHANG Xueli, LU Diangang, et al. Application of three-dimensional laser scanning technology in mining slope deformation monitoring [J]. Energy and Environmental Protection, 2023, 45(4): 67-68.

[5] WANG Jianjun, LI Yunlong, MIAO Song. Optics and Precision Engineering, 2018, 26(4): 788-795.

[6] LIU Jinjin, LI Haojun. Volume measurement of irregular objects based on improved point cloud slice method [J]. Acta Optica Sinica, 2021, 41(23): 133-145.

[7] ZHU Qing, WANG Dengxing, WANG Feng. Automatic measurement system of ship-borne sand volume based on LiDAR point cloud [J]. Journal of Southwest Jiaotong University, 2020, 55(6): 1199-1206.

[8] XU Zhi, XU Hongli. A fast volume calculation method based on convex hull approximation [J]. Computer Engineering and Applications, 2013, 49(21): 177-179.

[9] DONG Yahan, LI Yongqiang, LI Pengpeng. Tree crown contour point extraction and volume calculation based on improved convex hull algorithm [J]. Engineering of Surveying and Mapping, 2018, 27(8): 66-71.

[10] ZHUANG Zhengjie, WANG Liguang, GONG Yingzhong, et al. Rapid measurement of tank bottom displacement based on 3D laser scanning and convex hull algorithm [J]. Acta Metrology Sinica, 2018, 39(6): 852-856.

[11] LIU Jiazhen, LI Bin, YANG Chengsheng. Adaptive slicing method of irregular point cloud object with tangent distance and slice contour [J]. Laser Journal, 2022, 43(6): 66-68.

[12] ZHENG Guoqing, LV Pin, LAI Jizhou, et al. Automatic measurement method of target volume for unmanned vehicle based on LiDAR/vision [J]. Navigation Positioning & Timing, 2023, 10(2): 65-73.

[13] LIP Yong, JIANG Yong, ZONG Qiang, et al. Measurement and Calculation for stope volume of a gold mine based on laser 3Dscanning technique[J]. Metal Mine, 2018, 52(4): 145-149.

[14] YUE Kunming, ZHOU Dawei. Experimental study on truck load volume measurement in surface Mine based on TOF camera [J]. Metal Mine, 2023, 61(2): 167-172.

[15] HU Zhi-Xin, CAO LiU-Yang, PEI Dong-Fang, et al. Adaptive simplified point cloud improved preprocessing to optimize 3D reconstruction algorithm [J]. Advances in Laser and Optoelectronics, 2023, 60(20): 2028005.

[16] GUO Jianlin. Research on volume measurement of Karst cave using terrestrial dimension laser scanner[J]. Railway Investigation and Surveying, 2017, 43(6): 44-45.

[17] LIU Jing, JIN Yong, NING Hong Tao, et al. Research on cavity volume measurement method of laser point cloud solid rocket engine [J]. China Journal of Measurement and Testing, 2022, 48(04): 42-46.

[18] WU Jun. Research and development of surface reconstruction technology of scattered point cloud [D]. Shanghai Jiao Tong University, 2008.

[19] LU Xingzheng, XU Zhihua, XU Ershuai, et al. Calculation method of mine car loading capacity scanned by single line lidar[J]. Surveying and Mapping Bulletin, 2021(7):12-16.

[20] NING Xiaojuan, LI Jieru, GAO Fan, et al. Feature matching algorithm based on optimal geometric constraints and RANSAC [J]. Journal of System Simulation, 2022, 34(4): 727-734.

[21] LIU Feng. Proof and Application of Rodriguez Rotation Formula [J]. Jiangsu Science and Technology Information, 2020, (28): 37-40.

[22] ZHANG Yejiao, MA Liancheng, DUAN Jingang, et al. Experimental study on truck load volume measurement in surface Mine based on TOF camera [J]. Metal Mine, 2023, 57(2): 167-171.

[23] FAN Zhongmo, FENG Zhongke, ZHENG Jun, et al. Tree crown volume calculation and prediction model based on cubic body net method [J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 58(3): 320-327.

[24] JEREMIE Ndikumagenge, VERCUS Ntirandekura. Development of a Quantitative Prediction Support System Using the Linear Regression Method[J]. Applied Mathematics and Applied Physics, 2023, 57(2):421-427.