Object 3D surface reconstruction approach using portable laser scanner

Ning Xu¹, Wei Zhang², Liye Zhu¹, Changqing Li¹, Shifeng Wang††

¹ Changchun University of Science and Technology, Changchun, Jilin, 130022, China
² Shanghai Key Laboratory of Deep Space Exploration Technology, Shanghai Key Laboratory of Deep Space Exploration Technology, Shanghai, 201109, China

Abstract. The environment perception plays the key role for a robot system. The 3D surface of the objects can provide essential information for the robot to recognize objects. This paper presents an approach to reconstruct objects' 3D surfaces using a portable laser scanner we designed which consists of a single-layer laser scanner, an encoder, a motor, power supply and mechanical components. The captured point cloud data is processed to remove the discrete points, denoise filtering, stitching and registration. Then the triangular mesh generation of point cloud is accomplished by using Gaussian bilateral filtering, ICP real-time registration and greedy triangle projection algorithm. The experiment result shows the feasibility of the device designed and the algorithm proposed.

1 Introduction

Three-dimensional point cloud reconstruction theory and algorithm have been in an improved significantly recent years. However, most of the current researches are focused on the processing of static point cloud and the optimization of three-dimensional point cloud model, while the researches that are focused on point cloud real-time reconstruction technology are relatively less. However, the real-time processing of point cloud is particularly important in some areas like unmanned technology. In order to get a better application of three-dimensional point cloud reconstruction technology, the paper focused on point cloud data processing algorithm. Then an experimental platform was built to carry out experiments, which has achieved good results.

The main algorithms used in this paper are bilateral filtering, ICP real-time registration, and greedy triangle projection algorithm, which have respectively completed the removal of discrete points, noise reduction filtering, registration, and meshing of point cloud. In addition, in order to achieve the purpose of real-time reconstruction, in the course of research, the wireless transmission between the laser radar and the upper computer should be used to realize the real-time return of point cloud data. The research is aimed to apply the three-dimensional point cloud reconstruction technology to the unmanned field, and it also proved the feasibility of this technology through experiments.

2 The device development and data acquisition

Only get two-dimensional spatial coordinate information can be got through single-lane laser scanner. Meantime, to obtain the three-dimensional point cloud data, the laser scanner must be made to rotate around the fixed point. In order to obtain the three-dimensional spatial data through the single-line laser radar, it is necessary to convert the two-dimensional data into three-dimensional data. According to the laser scanner scanning pitch angle and scanning characteristics, the two-dimensional coordinates of the scanning point should be set as \((\rho, \theta)\) as shown in Figure 1.
The polar coordinate system in the laser scanner scan plane is transformed into a spherical coordinate system under the influence of its own rotation. The laser scanner rotation angle is recorded as azimuth angle $\beta$, the polar coordinate system constructed by the radar scan line is $(\rho, \theta)$, and the coordinates of the scanning point can be expressed as

$$
x = \rho \sin \theta
$$

$$
y = -\rho \cos \theta \cos \beta
$$

$$
z = \rho \cos \theta \sin \beta
$$

The two-dimensional matrix data obtained is applied to the three-dimensional reconstruction, as shown in Figure 1. Any plane of the space can be scanned by the single-lane laser scanner through the rotation of the mechanical structure, so that any two-dimensional empty matrix data of arbitrary plane in the space can be obtained. At the same time, in order to obtain the relationship among the various planes, the angle of each plane need to be obtained, and in order to obtain two-dimensional data of each plane, the following structure diagrams shown in figure 2 is designed.

Figure 2: Schematic of portable laser scanner structure

In this paper, the deceleration motor and the photoelectric encoder are used to obtain the angle information of each scanning plane, and the value of angle can be calculated by reading the pulse number of the photoelectric encoder. In order to make the data acquisition equipment more portable and more convenient for collecting real-time point cloud data, the handle type structure was used to obtain the data, the appearance picture shows in Figure 3.

Figure 3: Laser scanner appearance

3 Point cloud noise reduction

3.1 Sources and effects
In the point cloud acquisition phase, some noise points in the point cloud data will inevitably appear. The sources of these noise points are mainly divided into two aspects. On the one hand, the factors like the defects of laser scanner itself, equipment operators lacking experience and environmental factors
that will interfere measurements such as rain, snow and haze as well as the surface properties changes of the measured objects will bring noise points to point cloud data. On the other hand, while collecting data, the laser scanner may disturbed by external interference, such as obstacles, line of sight block and so on. These factors may lead to the generation of outliers.

The presence of the noise points will have an incalculable effect on subsequent point cloud processing. The noise point affects the effective selection of feature points in point cloud registration, and also negatively affects the quality of triangular meshes in the process of triangulation. The removal methods of point cloud noise points will be described below.

3.2 Filtering

(1) Uneven density of point clouds needs to be smooth. (2) Outliers caused by occlusion need to be removed. (3) A lot of point cloud data needs to be streamlined (also known as point cloud sampling that is to remove some points in the areas with high density to improve point cloud processing efficiency without affecting the weight of the surface). (4) The removal of noise points.

The process of point cloud filtering is described as bellow:

First, the removal of point cloud outliers is based on the following method: set a point cloud \( \{x_i, y_i, z_i \}_{i=1,2,3,..} \), and choose a point \( P = \{x, y, z, \} \), to calculate its distance from each point in the set \( Q \) of neighboring points, and obtain a set \( D \) of distances. Calculate the average distance \( d_0 \) which represents the distance between point \( P \) and the points in set \( Q \). Normally, when there is no outlier and the distance from the surrounding point to the center point is short. Furthermore, the distance from the surrounding point to the center point fluctuates around \( d_0 \). However, the existence of the outlier point will destroy this law, the distance \( d \) from the outlier point to the point \( P \) will be significantly greater than the value of \( D \). Now suppose that the elements in \( D \) satisfy the Gaussian Distribution and the mean value is \( d_0 \) and the standard deviation is \( \sigma \). When \( |d_i - d_0| > 3\sigma \), the point is considered as an outlier and is removed from the point set \( Q \). In this way, all the points in \( Q \) are traversed and the outliers can be removed. Then move the location of point \( P \) so that point cloud data can receive similar treatment [1]. Figure 4 (a) and Figure 4 (b) are respectively the original image and an image showing the effect of removing the discrete points of the point cloud by the above-mentioned method. It can be seen from the images that the points of the cloud around the table are significantly reduced.

![Figure 4 (a): Raw data](image1)

![Figure 4 (b): Remove discrete points](image2)

After removal of the outliers, the point cloud surface maybe not smooth enough, in order to further optimize the point cloud model, the bilateral filtering [2] is needed to carry out. Bilateral filtering algorithm refers to the filtering algorithm in the field of digital image processing. The algorithm can suppress the noise of the target image under the condition of preserving the details of the image. Bilateral filtering is a kind of filter which can preserve the edge and reduce noise. The filter consists of two functions. One function is that the Euclidean distance determines the filter coefficients, and the other is that the pixel difference determines the filter coefficients [3].

Then the bilateral filtering denoising algorithm will be used to filter the point cloud. The algorithm corrects the position of the current point by taking the weighted average of the neighboring point coordinates. The influence factor \( w_i \) of the neighboring point on the current point decreases as the distance increases, which subjects to Gaussian distribution. Choose a point \( P = \{x, y, z, \} \), and compute its distances to each point in the set \( Q \) of neighboring points, and get the set \( D \) of distance. Figure 5 shows the probability density function of the weighting function.
Figure 5: Weighted value calculation function of probability density function

And use the weighted value calculation function that is the bilateral filter operator to calculate, and the bilateral filter operator is \([4]\):

\[
f(x, y) = \sum_{i,j} \omega(i,j) f(i,j)
\]

In the formula, \(S_{x,y}\) represents both the big and small neighborhoods of \((2N+1) \cdot (2N+1)\) of center point \((x, y)\).

And

\[
\alpha(i,j) = e^{-\frac{|g(i,j)-f(i,j)|^2}{2\sigma^2}}, \quad \omega(i,j) = e^{-\frac{|g(i,j)-f(i,j)|^2}{\sigma^2}}
\]

\(g(i,j)\) is the pre-processed image, \(f(x,y)\) is the filtered image, \(w(i,j)\) is the product of \(w_1(i,j)w_r(i,j)\) of the two-part coefficients, \(\sigma_x\) controls the spatial proximity factor, \(\sigma_r\) corresponds to the brightness similarity factor.

The concrete steps are in these ways, firstly, establish the Q neighborhood, then find Q points which are nearest to each point and compose them into a neighborhood group. Fit the plane of the neighborhood through normal vector estimation and the least squares method. Then define the plane as the tangent plane, and the unit normal vector of the tangent plane is the normal vector. When the tangent plane is found, the view plane should be defined, that is, all the points within the neighborhood are projected along the normal vector direction onto the tangent plane \(S\), and the distance between the points of each neighborhood and the points on the projection plane \(D\) is defined as the pixel value. In this way the three-dimensional point cloud model is converted to a gray image model, and the targeted image is processed by bilateral filter operator.

Since the bilateral filter operator can suppress pixels that are too different from the central pixel value, the output pixel value depends on the weighted merging of the neighborhood pixel values. In this way, a series of interference like cusps and spurious points as well as bilateral filtering, median filtering, mean filtering and Gaussian filtering can be effectively removed. It can be seen from the following experiment that the scheme has strong applicability and moderate speed, so the operator is chosen to deal with the target image.

| Filter            | Points before filtering | Points after filtering | Percentage   |
|-------------------|-------------------------|------------------------|--------------|
| Bilateral filter  | 41049                   | 38235                  | 93.144%      |
| Median filter     | 41049                   | 40021                  | 97.496%      |
| Mean filter       | 41049                   | 36767                  | 89.569%      |
| Gaussian filtering| 41049                   | 39490                  | 96.202%      |

Table 1: Different filtering of the data analysis was carried out on the table
The above table is used to carry out filter the experiment. Through experiments, we found that although the mean filter speed is high, but some of the important features of point clouds will be filtered out, and the noise can only be weakened but not removed. Although median filtering can guarantee a sharp portion, it is slower for a large number of data points. Compared with bilateral filtering algorithm, Gaussian filtering has a good performance in the low-pass filter algorithm. But it has another problem-only the relationship between the spatial positions of the pixels is considered, so the result will lose some edge information. And Bilateral adds another Gaussian weight which is based on the spatial similarity in Gaussian blur to solve this problem. As for the speed, Gaussian filtering is faster, and the bilateral filter is not like ordinary Gaussian filter (convolution low-pass filter) which only consider the position of the central pixel. It also considers the effect of the similarity between the pixels in the convolution kernel and the central pixel, and the two algorithms are different in the choice of the weight function. Therefore, in order to achieve the effect of three-dimensional point cloud real-time reconstruction, compared to other noise reduction filtering algorithms, moderate speed and retention feature are the advantage of this algorithm.

4 Splicing
Due to the complexity of the spatial structure of the three-dimensional entities and the limited viewing angle of the laser scanner, the laser scanner usually can’t obtain a complete point cloud at a fixed scanning site. In this case, it is necessary to change the position of the laser scanner and scan the target with a multi-site scan. In the process of moving, on one hand, the data obtained by laser scanner scanning different sites are distributed in different radar coordinate systems and can’t be directly used to reconstruct three-dimensional entities; on the other hand, the measurement error of the position by the laser scanner is inevitably. This error is likely to accumulate over time, and the errors will result that inter-site point cloud data can’t be well connected. In order to solve the above problem, we need to register the point cloud data.

Point cloud registration is based on two coordinate systems, absolute coordinate system and global coordinate system. The local coordinate system is the spherical coordinate system constructed by the laser radar when it is rotated. It is used to describe the local point cloud information. The task of point cloud registration is to transform the local point cloud to the absolute coordinate system, and realize the integration of point cloud information.

4.1 The traditional ICP algorithm
ICP algorithm is derived from a paper published by Besl in 1992. The algorithm assumes that the point in the source point cloud corresponds to the target point cloud, and the two are the inclusive. The distance between the corresponding point pair is the objective function. The optimal rotation matrix R and the translation matrix T are found by using the least squares principle, and the target function value is minimized. At this time, the two point clouds are registered to the same coordinate system. As the iteration is carried out step by step, it is computationally intensive and time-consuming, and the computing time increases with the increase of the point cloud data.

On the other hand, the classical ICP algorithm simply determines the point pair with the closest Euclidean distance as the corresponding point, which may lead to improper selection of the corresponding point and cause local optimum. In order to solve this drawback, later researchers has improved the classic ICP algorithm from different aspects. They used features to find the corresponding point, which reduced the amount of operations and iterative times, thus the accuracy and efficiency of ICP algorithm has been greatly improved. The improved ICP algorithm is discussed below. Figure 6 shows a comparison of the two ICP algorithms.
4.2 ICP algorithm for feature extraction

The improved ICP algorithm firstly extracts the similar feature and finds the corresponding point pair. Then calculates the sum of the Euclidean distances of the corresponding point pairs, set the thresholds and iterations and use the least squares method to find the rotation translation matrix, rotate the translation, and iterate through the loop until the distance is less than or equal to the threshold. There are many methods for selecting features, such as the angle between normal vectors, curvature and gradient.

It should be noted that both the classical ICP algorithm and the improved ICP algorithm require the registered two-point clouds have overlapping regions, so that it is possible to find the relationship between the two to register.

In addition, the ICP algorithm needs to set a reasonable threshold as the termination condition of the iteration. The smaller the threshold is, the higher the precision of registration is and the longer the corresponding computing time will be. Thus, this threshold needs to be carefully selected. Otherwise if threshold is too large, there will be a large gap or rotation dislocation in the two point clouds, and if the threshold is too small, the unnecessary memory space and computing time will be wasted. At the same time, because the feature is extracted first, the matching point cloud is limited to the overlapped part, and the number of iterations is greatly reduced. Figure 9 is point cloud the splicing effect diagram for the two kinds of ICP algorithm. It can be seen that the traditional ICP algorithm is arbitrary, and the improved ICP algorithm will carry out point cloud matching according to the normal vector in the graph. It can be seen from Figure 9 that the ICP algorithm after feature extraction is significantly better than the traditional ICP algorithm.

5 Greedy triangular projection

After using the above-mentioned ICP algorithm, the spliced point cloud is obtained. The delaunay algorithm will be used to carry out triangular mesh reconstruction for the spliced point cloud. Because the three-dimensional delaunay algorithm will make the irrelevant clutter triangles generate in the middle of the point cloud shell model due to triangulation, which will not only affect the appearance, but also lose the characteristics of three-dimensional model of the entity. So greedy triangular projection algorithm will be used to avoid this error. The specific method is as follows: then establish neighborhood k, that is the k points which are nearest for each point and put them into a neighborhood group of normal vector which is estimated by least squares. Fit the tangent plane of the neighborhood plane, and the unit normal vector of the tangent plane is the normal vector of the point. All the points in this neighborhood are projected in normal direction to the tangent plane. Then the points on the tangent plane are delaunay triangulated to obtain the topological relationship between point clouds and to construct a triangular mesh in three-dimensional space by using topological relations.
The three-dimensional point cloud can’t be triangulated with Delaunay directly, because the function simply uses the distance and the angle relationship between the points as the basis for constructing the triangular mesh, which is likely to lead to the disordered connection of the model surface points, resulting in some of the long and narrow messy triangle\[^{11,12}\]. Greedy triangular projection algorithm transforms the three-dimensional triangulation of the three-dimensional to two-dimensional space, then reconstructs the model according to the topological relation in the corresponding three-dimensional point cloud, which can effectively avoid the generation of clutter triangles. Figure 10 shows the table effect of greedy triangular projection.

![Figure 8: Greedy triangular projection of the table](image)

**6 Conclusion**

This paper has presented an object 3D Reconstruction method using point cloud data. The portable device has been designed and developed applied a sing-layer laser scanner, in which a motor along with an encoder are employed to obtained angular information while the laser scanner is rotating. The Kd-tree algorithm can extremely improve the point cloud data search speed and subsequent processing. The greedy triangle algorithm is then applied in the stage of point cloud visualization, which can project original 3D point cloud data into 2D plane, as well as the topological connection of those points. Due to the higher efficiency than the traditional seed algorithm, this method helps to improve the computing speed. However, the approach presented need to be optimized and improved. And quantifiable estimation is also considered to establish in the future work.

**Acknowledgements**

This work is funded by National Natural Science Foundation of Jilin Province (20150101047JC), Changchun University of Science and Technology (CUST) for Young Scholar (XQNJJ-2014-05), Funding of Science and Technology Commission of Shanghai Municipality (13dz2260100), National Key Basic Research Program of China (2014CB744200), and Open Projects of Shanghai Key Laboratory of Deep Space Exploration Technology (DS201509-002, DS201507-001). This work is also supported by OptoBot Lab and Opto-Electronic Engineering School of CUST.

**References**

[1] Radu Bogdan Rusu, Nico Blodow, Zoltan Marton, et al. “Towards 3D Point cloud based object maps for household environments”, *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, 46, pp. 3191-3198, (2007).

[2] C. Tomasi, R. Manduchi. “Bilateral Filtering for Gray and Color Images”, *International Conference on Computer Vision*, 34, pp. 839 - 846, (2016).

[3] G. Ramponi. “A rational edge-preserving smoother”. *In Proc. Intl-ConfonImage Processing*, 1, pp. 151-154, (1995).

[4] L. Hajder and D. Chetverikov. “Weak-perspective structure from motion for strongly contaminated data”, *Pattern Recogn. Lett.*, 27, pp. 1581-1589, (2006).
[5] Du Xiaoyan, Jiang Xiaofeng, Hao Chuangang, et al. “Bilateral filtering denoising algorithm for point cloud model”. *Journal of Computer Applications and Software*, **27**, pp. 245-264, (2010).

[6] P.J. Besl, H.D. Mckay. “A method for registration of 3-D shapes”. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **28**, pp. 239-256, (1992).

[7] Martin Magnusson. “The Three-Dimensional Normal-Distributions Transform-an Efficient Representation for Registration”, *Surface Analysis and Loop Detection*, **43**, pp. 254-287, (2013).

[8] Yang Qiuxiang, Wang Chengyuan, Yang Jian et al. “Based on the method of vector Angle improved ICP algorithm”. *Computer engineering and design*, **37**, pp. 2082-2086, (2016).

[9] Zoltan Csaba Marton, Radu Bogdan Rusu, Michael Beetz. “On Fast Surface Reconstruction Methods for Large and Noisy Point Clouds”. *IEEE International Conference on Robotics & Automation*, **28**, pp. 3218-3223, (2009).

[10] D. Grable, “On random greedy triangle packing”, *Electronic Journal of Combinatorics*, **19**, pp.9, (2007).

[11] V. Rodl, “On a packing and covering problem”, *European Journal of Combinatorics*, **24**, pp. 69-78, (2009).

[12] N.C. Wormald, “The differential equation method for random graph processes and greedy algorithms”, in Lectures on Approximation and Randomized Algorithms (M. Karonskiand H.J. Promel, eds), pp. 73–155, (2011).