Point Cloud Registration Method for Pipeline Workpieces Based on 4PCS and Improved ICP Algorithms

Shan Xue, Guangqing Li, Qiongying Lv*, Xianyu Meng, Xin Tu
Changchun University of Science and Technology, Changchun, China

*Corresponding author e-mail: 1660348815@qq.com

Abstract. A new point cloud registration method based on 4PCS and improved ICP algorithm is proposed to solve the problem of point cloud registration of laser scanning workpiece position and pose data on industrial pipeline. Firstly, feature points set of point cloud is extracted from normal vector. Then, the rough registration of point cloud is realized by using the registration algorithm based on feature points (4PCS), and the initial recognition of workpiece position and pose is completed. Finally, based on the traditional ICP algorithm, the k-d tree is used to accelerate the search speed of the corresponding point pairs and complete the accurate registration of the point clouds. The proposed algorithm and the 4PCS+ICP algorithm are tested respectively, and the results show that the algorithm is faster, with lower error and fewer iterations.

1. Introduction

In recent years, with the continuous progress of optical measurement technology and point cloud data processing technology, point cloud data obtained by laser scanning, as a carrier containing real three-dimensional information of object surface, has attracted widespread attention [1]. The point cloud registration technology is the key problem of three-dimensional reconstruction in robot navigation, reverse engineering, computer vision and other fields. And it is also one of the key technologies of workpiece pose recognition on pipeline. How to use point cloud registration technology to identify workpiece pose on pipeline has become a hot topic of more and more scholars.

At present, the most widely used registration point cloud algorithm is the nearest point iteration algorithm ICP proposed by Besl and Mpy [2, 3]. It searches for the optimal matching of the target point set and the reference point set by constantly searching for the optimal rigid body transformation matrix of the two point cloud. However, ICP algorithm is easy to fall into the local optimal solution when the initial position of point cloud data set varies greatly and there is no inclusion relation. To solve this problem, a new point cloud registration algorithm based on 4PCS and improved ICP algorithm is proposed. First, the 4PCS algorithm is used to initial registration of two point clouds, and the transformation matrix is used as the initial estimation of the ICP accurate registration algorithm. In precise registration, k-d tree nearest neighbor search method is used to improve the speed of searching corresponding point pairs and the efficiency of the algorithm when ICP algorithm is used.
2. Using Normal Vector to Extract Feature Point Set

The number of point clouds in original point clouds is large and the model is complex. Using normal vectors to extract feature points sets to simplify the number of point clouds can reduce the workload of subsequent algorithms, improve work efficiency and reduce errors.

The normal vector of a point represents the normal vector of the local plane centered on this point. According to the change of the angle between the normal vectors, the curvature of the surface can be observed very simply. As shown in the following figure, the angle between normal vectors is large, which indicates that the fluctuation of the plane area is relatively large; the angle of the normal vector is small, indicating that this area is relatively flat. Therefore, it is effective to select the points with large variation of normal vectors as the feature points set of this region.

![Normal vectors in different regions.](a) Large undulating area (b) Gentle area)

Figure 1. Normal vectors in different regions.

A point $p_i$ in an arbitrary point cloud is selected and define the characteristic degree [4] of the point as the arithmetic mean of the angle between the normal vector of the point and the normal vector of all points in the k-field.

$$ f_i = \frac{1}{k} \sum_{j=1}^{k} \theta_{ij} $$  \hspace{1cm} (1)

In the formula, $\theta_{ij}$ is the angle between the point $p_i$ and its adjacent point $p_j$, normal vector, and $f_i$ is the arithmetic average of the angle between the point $p_i$ and its $k$ adjacent point normal vectors. Some point clouds are removed by setting the threshold of $f_i$, leaving behind the point clouds with large fluctuations in the region. The selected feature set is shown in Fig.2.

![Comparison of feature points before and after selection.](a) Primary characteristic point cloud (b) Selected feature point set)

Figure 2. Comparison of feature points before and after selection.
3. Rough Registration Based on 4PCS Algorithm
Given the reference point cloud P and the target point cloud Q, four coplanar points in P are selected to form a set of base M. Using affine invariance constraints, all corresponding point pairs N that may meet the matching conditions are found in the reference point cloud P, and the transformation matrix $F_i$ of each set of corresponding point pairs N and base M is calculated. Calculate $F_i(P)$ and find out the number of points whose distance from the point on Q is less than a preset threshold (set to twice the average distance between points). The transformation matrix with the largest number is chosen as the optimal solution.

Figure 3. Four-point coplanar basis \{a,b,c,d\}.

\[
R_1 = \frac{|a-b|}{|a-e|} \quad (2)
\]
\[
R_2 = \frac{|c-e|}{|c-d|} \quad (3)
\]
\[
e_1 = q_i + R_1(q_j - q_i) \quad (4)
\]
\[
e_2 = q_i + R_2(q_j - q_i) \quad (5)
\]

As shown in Fig. 3, firstly, three coplanar points are randomly selected in the reference point cloud P. The fourth point selected should be far away from the three points. The selection of long baseline can ensure the robustness of matching and the number of matching is small. Selecting a group of coplanar bases \{a,b,c,d\} , ab and cd will intersect at point e. The scaling coefficients $R_1$ and $R_2$ are calculated by Formula (2) and (3). The two scaling coefficients have invariance in the rotation and translation of point clouds.

Two points are selected in the target point cloud. These two points form a line segment. According to the ratio of $R_1$ and $R_2$, the possible coincidence point e on this line segment can be known. Taking this line segment as a baseline and the known overlap point, according to Formula (4) and Formula (5), look for another possible baseline in the point cloud and get the other two possible corresponding points. These four points are a corresponding transformation of the basis \{a,b,c,d\} . Calculate transformation matrix and complete rough registration.

4. Accurate Registration Based on Improved ICP Algorithm
The nearest point iteration algorithm ICP proposed by Besl and Macay is used in this paper. ICP wastes a lot of time in searching for the nearest point, and has high requirements for the location and inclusion relationship of the registration point cloud. In order to solve this problem, a new method is proposed in this paper. The k-d tree nearest neighbor search method is added on the basis of ICP, which can speed up the query of corresponding point pairs, improve the accuracy of transformation matrix between each corresponding point set, and improve the efficiency of registration.

The steps of using ICP algorithm are as follows: firstly, two point clouds Q and P'(the position of point clouds P after initial transformation) after initial registration of 4PCS algorithm are used as the
initial position of ICP accurate registration; the second, for each point \( q_i \) in reference point cloud, the corresponding data point \( p_i \) in target point cloud is searched, requiring the minimum Euclidean distance between the two points; then, the rigid body transformation parameters of two point clouds are calculated. The rotation matrix \( R \) and translation matrix \( T \) are obtained to minimize the mean square error \( d_k \) of the corresponding point set.

\[
d_k = \frac{1}{n} \sum_{i=1}^{n} \| q_i - (Rp_i + T) \|^2
\]  

(6)

Finally, if the difference between two consecutive mean square errors \( d_k \) is less than the preset threshold or the number of iterations is greater than the preset number of iterations, the iterations are stopped and the rotation matrix and translation matrix are output. Otherwise, continue to iterate, transform the target point cloud several times, and finally get the value that satisfies the condition. The most tedious task of ICP is to find the nearest point in point cloud, and k-d tree is an effective way to solve this problem.

K-d tree is an effective data structure for spatial query in multi-dimensional space. It can effectively improve the search efficiency of adjacent points in a large number of three-dimensional point clouds. ICP spends a lot of time searching adjacent points, resulting in low computational efficiency. The use of k-d tree effectively solves this problem and improves the computational efficiency of ICP.

K-d tree is divided into left and right subtrees. Comparing the data points to be queried with the value of the root node, if it is less than or equal to entering the left subtree, if it is larger than entering the right subtree, it will be executed until the leaf node of the k-d tree. Find the nearest neighbor similarity points on this subspace, and then return the points. If the subspace of other nodes has closer points, then jump to the subspace nodes to find the nearest points. Repeat this operation to find the nearest point until the search path is empty.

5. Experiments and Analysis

In order to verify the effectiveness of the proposed algorithm, simulation experiments are carried out in MATLAB software. Using the bunny model provided by Stanford University website as a template, a comparative experiment between the traditional ICP algorithm and the algorithm in this paper is carried out. In the experimental platform Intel (R) Core (TM) i5-4200M CPU, 8GB memory Win8 system, using MATLAB 2018a software. The experimental results are shown as follows.

Figure 4. Diagram of point cloud registration.
The 4PCS+ICP algorithm registration and the algorithm registration of the point cloud are respectively performed on the point cloud. It can be seen from Table 1 that the algorithm has fewer iterations, less running time and less registration error. The rotation and translation matrices obtained by the two methods are shown in Fig. 6.

**Table 1.** Comparing the experimental data of two algorithms.

| Method                              | Iteration times | Running time/s | Registration deviation |
|-------------------------------------|-----------------|----------------|------------------------|
| 4PCS+ICP algorithm                 | 18              | 19.211278      | 0.4962                 |
| Algorithm in this paper            | 9               | 1.260567       | 0.0163                 |

**Figure 5.** Display diagram of registration results in 3d coordinate system.

**Figure 6.** The rotation matrix and translation matrix and time result graph are obtained by the two algorithms.
6. Conclusion
A new point cloud registration method based on 4PCS and improved ICP algorithm is proposed in this paper. Firstly, a threshold is set to get the feature points set of point clouds by using the normal vectors of point clouds, which reduces the number of point clouds, reduces the workload of the algorithm and improves the operation efficiency. Then, the point clouds are initially registered by using 4PCS algorithm, so that two point clouds can obtain better initial positions. Finally, the k-d tree nearest point search method is added on the basis of the classical ICP to improve the efficiency of ICP operation and save time. Compared with 4PCS + ICP algorithm, the experimental results show that the proposed algorithm has faster running speed, better matching accuracy and fewer iterations.

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