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Improved ICP Point Cloud Registration Based on KDTree

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Abstract: Based on the analysis of the principle of ICP and KDTree algorithms, the paper summarized the defects of ICP and the advantages of KDTree, and with KDTree characteristics proposed fast traversal search nearest neighbor point set to form same name points, then the registration is realized to calculate transformation parameters R and T by Four Element method. Through verification of measured data and simulated data, it has been significantly improved in time and efficiency for the improved ICP algorithm based on KDTree algorithm which related to traditional ICP algorithm. This method enriches Terrestrial 3D laser scanning technology and registration technology. It will play an important role in the field of Geographic Information Science, Remote Sensing image processing, Reverse Engineering.

Keywords: *Point Cloud Data Registration, ICP, KDTree, Four Element Method*

1. Introduction

Because of the field limitation of view and the practical application necessity, it is difficult for Terrestrial 3D Laser Scanning System (TLSS) to obtain the complete information of the object surface. It needs to scan the surface of the entity from different locations. So, the different positions scans need to be matched to the same coordinate system to fully reflect the object surface information, which is required to find a reliable and accurate data registration algorithm to realize the point cloud fast matching. Registration technology has important applications in the field of Geographic Information Science (GIS), Remote Sensing image processing, quality detection, face recognition, fingerprint recognition and image mosaic in archaeology.

As the core technology of Terrestrial 3D Laser Scanning (TLS), the method of point cloud data registration is various. It can be divided into two categories: one is that using a special target point cloud is matched by extracting target center as homonymous points; the other is the same point is found in the nearest public area to point cloud registration. Because need to decorate the target, the manual intervention is much, the automation degree is low, the former increases the burden of the internal and external work. The latter is a higher automation degree, especially Iterative Closest Point (ICP) algorithm [1] is proposed by BESL et al., which is currently the most widely used.

2. Defects of traditional ICP algorithm

The basic idea of the ICP algorithm: the assumption that the target point set P (object need to coordinate transformation) and the set of reference point set Q, P and Q need to be matched. The first, the mapping relations is established for each point in P and a nearest point finding in Q; the second, the optimal coordinate transformation (Recorded as M) is calculated by least squares method, and P = M(P), and get a result by the iterative method until meet the accuracy; the end, the final coordinate transformation is each time synthesis transform. In the actual use, this traditional ICP algorithm theory has a lot of shortcomings, as follow:

(1) It is only applicable to a clear positioning relation between the point sets. Namely, a point set is a subset of another point set. In other words, there is a relationship or overlap between the 2 point sets. When this condition is not satisfied, it will affect the convergence results of ICP, and produce the wrong matching.
(2) It is higher requirements for ICP algorithm to the relative initial location of the 2 point cloud. The distance is not too large for the initial position between the point clouds. When the position is too large, it is necessary to initial registration of the original point cloud, otherwise the convergence is uncertain.
(3) If the distance between the point and point of the overlapped area is too large, ICP could not find the corresponding point pair, or appear the phenomenon of one to many, many to many. This caused the iteration of the algorithm could not be achieved.
(4) Since every time iteration is required to compute corresponding point of the reference point with each point of the target point, the computation workload is very large and the computation speed is very slow.

In view of the above shortcomings, many domestic and foreign scholars have put forward some beneficial improvement plan. Masuda [2] uses random sampling to extract reliable point sets from the first point, and then find the corresponding points in the reliable point set. CHEN[3] calculates the minimum cut plane distance of the corresponding point between the point of first view and second view to coordinate

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transformation of the solution. The advantage is that the point in the two views does not need to be a one-to-one correspondence. But the method needs to solve a nonlinear least squares problem, the speed is slow. Combining the inverse calibration method and random search method, BLAIS et al. [4] improve the computation speed, but it will have a certain impact on the registration accuracy. Based on ICP algorithm, BESL proposed a fast ICP algorithm, which can solve the matching problem of data points of 6 freedom degrees and model. But every time iteration of the algorithm needs to calculate the shortest distance of point to the model, and the processing is slow speed [1]. FAN et al. take the direct method to calculate the shortest distance of the data points to the reference model, and then use the least square method to calculate the translation vector and rotation angle, but the method is only applicable to a simple reference model [5]. LI proposed Iterative Closest Line (ICL) on the basis of ICP and Iterative Closest Triangle (ICT) algorithm. The algorithm directly make two data points line or triangulation, and then according to certain criteria to find approximately the corresponding line or triangular patch in the two views. The advantage is that it is no requirement for the initial position of the two views, and the disadvantage is that the correspondence between the line segments can't be guaranteed [6].

3. Traditional ICP improvement ideas

For large scenes of ancient architecture and archaeology, the point cloud data is huge through TLS measurement, and it is a discrete and nontopological relation, which will be very difficult for the traditional ICP to match by traversal search corresponding points. Therefore, it is the key for the geometric topology (spatial location) between point sets of point cloud data to improve traverse search speed in dense discrete point set. The point cloud data registration must establish the neighborhood structure between point sets.

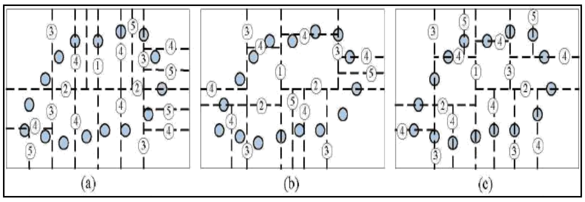
Since the construction time of KDTree [7] is O(nlogn), and the time is O(k+logn) to traversal search k nearest neighbor points, and the insertion and update time of single point is O(logn) [8], its fast speed and high efficiency cannot be compared to other search methods.

In summary, the defects of the traditional ICP algorithm, the improved strategy is as follows: First, the point cloud data is roughly registered (rough matching), which is to prevent the initial position deviation is too large; then to find the nearest point to solve traditional ICP slow speed by KDTree, which is the fast search characteristics; Final, to calculate the parameters R and T by using Four Element method and achieve precise matching.

4. KDTree traversal search algorithm

4.1. KDTree Principle

KDTree was first proposed by the Bentley [9] who extended the two fork search tree to high dimensional space, and later Freidman [10] and Sproull [11] et al. developed it. For point cloud data, the equilibrium method is used to divide the plane and construct the balanced [12] KDTree. As shown in Figure 1.



(a) Midpoint segmentation. (b) Balanced tree. (c) Sliding midpoint method. Figure numbers indicates hierarchy of the current node in the KDTree.

Figure 1: *KDTree structure Principle*

Its basic principles are as follows: On the assumption of n point in the point set P of the plane, the plane is divided into 2 rectangular (bounded or unbounded) by the straight line alternating parallel to the X axis or Y axis, and the straight lines have a point in the P, there are about the same points on both sides of the straight line. The rectangle is $[x_1, x_2][y_1, y_2]$ of Cartesian product by X interval $[x_1, x_2]$ and Y interval $[y_1, y_2]$ (Taking two dimensional as an example), the x_i, y_i (i=1, 2) is $-\infty$ or $+\infty$ [13]. And so on, until there is only one point in the region. The segmentation process is equivalent to the corresponding two-dimensional binary tree, as shown in Figure 1. Figure 2 is an example of when n=11.

The method can be extended to K dimension (k>2), which is to consider the segmentation of hyper plane orthogonal to coordinate axes, and to select the direction criterion for the segmentation of hyper plane. Figure 3 shows the space 3D point cloud process 3 times segmentation. The white lines show the root bounding box. The heavy black lines form 2 small bounding boxes after the first time division. The black wire lines form 4, form 8 dotted lines. These small bounding boxes called sub bounding box.

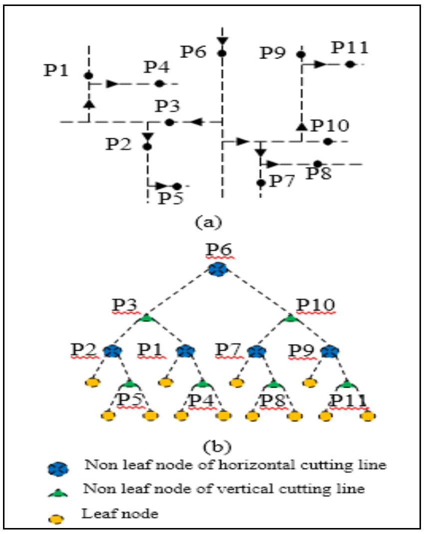


Figure 2: *Balanced KDTree segmentation process*

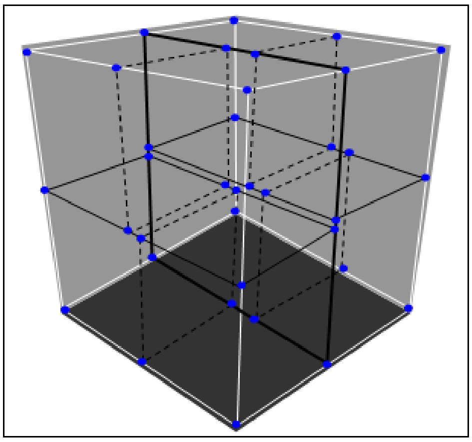


Figure 3: *Spatial 3D point cloud segmentation process*

4.2. Traversal search nearest neighbor point set based on KDTree

The neighborhood point set is also called the k nearest neighbor, which is the nearest K point set. Finding k closest points in a certain point set, the process is called the nearest neighbor search or k nearest neighbor search, which widely used in reverse engineering, geographic information, neural network, computational geometry, image recognition and other fields.

For the scattered point cloud data obtained from 3D laser scanning measurement, the topological relationship between the point sets of point cloud data is established by using KDTree structure. In the KDTree structure, it is efficient and quick for a point to search or traversal in the nearest neighborhood point set by eliminating search space. The process of KDTree searching for the neighborhood point set is as follows:

(1) From the root node, the algorithm is moved to the KDTree spatial structure. If the search point is inserted into, same operation is as before (Determine whether the value of the point is greater than or less than the value of the current node on the split plane to decide to move or insert to the right or to the left).

(2) If the algorithm moves down to the leaf node, then it save the current node as the best point.

(3) Opening KDTree recursive algorithm, the following steps will be executed on each node:

1) If the current node is closer than the best point saved, then the current point is replaced by the best point.

2) To determine if there is closer for any point on the other side of the split face than the search point, and is also adjacent to the best point of the current, which would be finished by the intersection judgment of the segmentation plane and sphere (The segmentation sphere is generally based on the search point as the center of the sphere, the distance of search points from the current nearest point as the radius of the sphere).

3) If the split sphere and the split plane have intersection, the other side of the split face may be the nearest point, the algorithm must move from the current node where KDTree branch to another branch to search for a more recent point; If the split ball does not intersect with the separating plane, the algorithm continues to run along the current KDTree branch, and the other side of the split plane of the current node is eliminated.

(4) When according to the search process of the root node, the algorithm completes the search of all nodes, the whole node traversal search is end, and the neighborhood point set is established.

5. Improved ICP Algorithm Based on KDTree

5.1. Search the corresponding point based on KDTree

Applying ICP registration for multi view cloud data from scanning large scenes, it requires 20% overlapping regions between the adjacent point cloud data to ensure to find the corresponding point enough. According to the principle and algorithm of KDTree traversal search nearest neighbor point set, when points k=1 in the neighborhood point set, the one-to-one relationship can be established between the search point and neighborhood point, and their distance is the smallest distance in which the distances are from the search point to other neighborhood points.

5.2 Calculate transformation matrix by four element method

In ICP registration, the transform parameters (rotation matrix R, translation matrix T) have a many methods, such as Euler Angle, Rotating Shaft and Rotation Angle, Four Element method, etc.. The Four Element method, whether in R, T calculation accuracy or speed, has a great advantage. In addition, in the ICP registration, it is commonly used. Its algorithm flow is as follows:

(1) Calculate barycentric coordinates of the two point set S, P, and recorded as L1, L2.

(2) Point cloud barycentralization:

According to the formula

$$\overline{X} = x_i - \frac{\sum x_i}{n}, \overline{Y} = y_i - \frac{\sum y_i}{n}, \overline{Z} = z_i - \frac{\sum z_i}{n}, i = 0,1,2...n,$$

, point cloud can be gravity-centralized.

(3) Construct the N matrix, thereinto:

$$N = \sum_i \begin{bmatrix} x_{si}x_{pi} + y_{si}y_{pi} + z_{si}z_{pi} & y_{si}z_{pi} - z_{si}y_{pi} & z_{si}x_{pi} - x_{si}z_{pi} & x_{si}y_{pi} - y_{si}x_{pi} \\ y_{si}z_{pi} - z_{si}y_{pi} & x_{si}x_{pi} - y_{si}y_{pi} - z_{si}z_{pi} & x_{si}y_{pi} + y_{si}x_{pi} & x_{si}z_{pi} + z_{si}x_{pi} \\ z_{si}x_{pi} - x_{si}z_{pi} & x_{si}y_{pi} + y_{si}x_{pi} & -x_{si}x_{pi} + y_{si}y_{pi} - z_{si}z_{pi} & z_{si}y_{pi} + y_{si}z_{pi} \\ x_{si}y_{pi} - y_{si}x_{pi} & x_{si}z_{pi} + z_{si}x_{pi} & z_{si}y_{pi} + y_{si}z_{pi} & -x_{si}x_{pi} - y_{si}y_{pi} + z_{si}z_{pi} \end{bmatrix} \quad (1)$$

(4) The characteristic value of matrix N is calculated, in which the maximum characteristic value is obtained, and the corresponding characteristic vector is calculated, recorded as (W, X, Y, Z).
(5) Constructing the rotation matrix R:

$$R = \begin{bmatrix} 1-2(Y^2+Z^2) & 2(XY-WZ) & 2(WY+XZ) \\ 2(XY+WZ) & 1-2(X^2+Z^2) & 2(YZ-WX) \\ 2(XZ-WY) & 2(YZ+WX) & 1-2(X^2+Y^2) \end{bmatrix} \quad (2)$$

(6) Calculation translation T:

T=L2-R'*L1 (3)

5.3. Improved ICP algorithm based on KDTree

According to the above analysis, this paper improved ICP algorithm based on KDTree, its steps are as follows:

(1) In point cloud, the overlap of point set P and Q is defined as reference point set P' and target point set Q '.
(2) Assuming k=1, in point set Q', the algorithm searches nearest neighbor points for any point of point set P', and get corresponding points only for any point in P '. That is, there is set point $P^m = \{P_1^m, P_2^m, \cdots, P_n^m\}$ in P' which correspond point set $Q^m = \{Q_1^m, Q_2^m, \cdots, Q_n^m\}$ in Q ', the point set Pm and Qm can be found by KDTree, the m represents ICP iterates m times.
(3) To set minimum distance threshold d, delete error corresponding point pairs in P^m and Q^m, and update P^m and Q^m.
(4) To calculate *R*, *T* of Pm and Q^m by Four Elements method.
(5) Using *T* and *R*, the point set Pm is transformed, and the updated Pm is obtained;
(6) Repeating (2) to (5) steps, they are calculated for corresponding points in the point set Pm and point set *Q*, and *R*, *T*.
(7) After the registration, the coordinate difference of the corresponding points is used as threshold which is the convergence condition. When obtain R, T meeting the accuracy requirements, the cycle is end and the registration is success. Otherwise, from the beginning of (2), the m+1 iteration are carried out.

Figure 4 showed the software design process of the improved ICP algorithm based on KDTree.

6. Improved ICP algorithm Verification Based on KDTree

6.1. Algorithm implementation by VC++ and Matlab software

The implementation of KDTree is in the form of VC++ class. Matlab software realized improved ICP algorithm. In matlab software, the KDTree class was called by the sentence of " mex KDTree.cpp". Thus the improved ICP algorithm based on KDTree is realized.

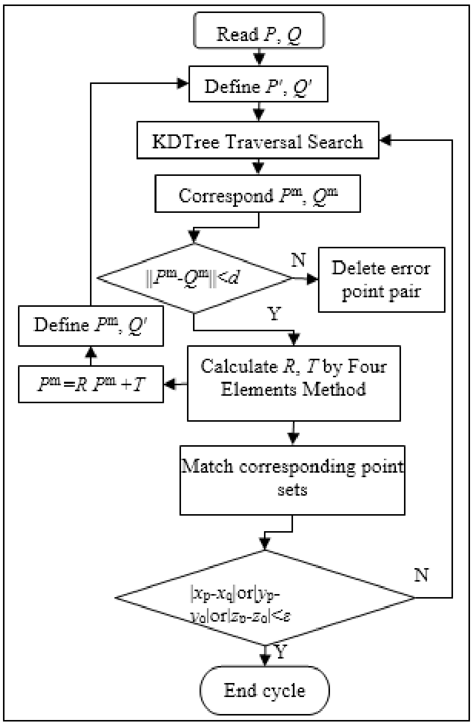


Figure 4: *The software design process of the improved ICP algorithm based on KDTree*

6.2. Algorithm verification of measured point cloud data

(1) Took a building as a case, set the two station scanning, the point cloud of the building was collected in the condition that sampling interval is 1cm, overlap area is about 40%;
(2) Figure 5 and 6 shows the non-registration point cloud picture of the two site point cloud data in the same coordinates. In the Figure 5, the dark point cloud is the first station, the number is 19727, light color is the second station, the number is 18764.

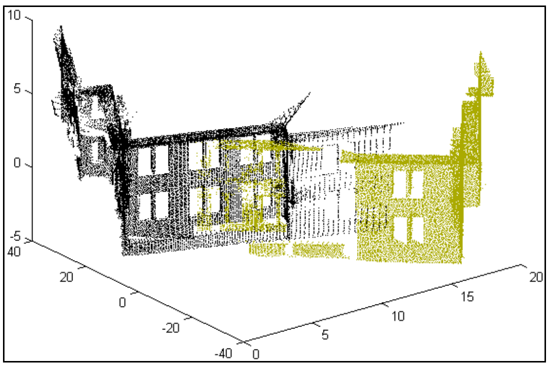


Figure *5: the non-registration point cloud picture*

(3) Through 47 times iteration of the improved ICP algorithm based on KDTree, Figure 6 is the registration result of two group of point cloud data which took 1.341 seconds.

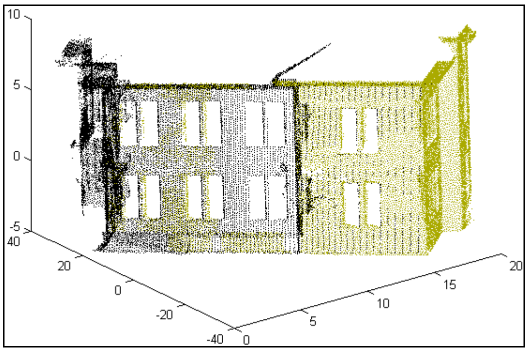


Figure 6: The registration result by Improved ICP algorithm based on KDTree

7. Conclusion

In the above case, the feasibility of the improved ICP algorithm has been verified. The paper matched the case point cloud data by traditional ICP and found it took 36.322 seconds, which have bigger difference with 1.341 seconds. In addition, the paper compared traditional ICP and Improved ICP by simulated data. Table 1 can be seen, there is a big difference in the calculation time with the increase of the number of points. Especially when the large amount of point cloud data registration, the improved ICP algorithm has obvious advantages in the registration efficiency and time.

Table 1: *Comparison between traditional ICP and improved ICP algorithm*

Point numbers	Registration Time (unit: second)	
	Traditional ICP	Improved ICP
5000	4.231	0.532
10, 000	28.452	1.012
50, 000	256.336	2.731
100, 000	1243.983	14.320
150, 000	8953.431	33.121

8. Acknowledgements

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