A 3D Point Cloud Registration Algorithm based on Feature Points

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Keywords: 3D point cloud registration, feature points, ICP algorithm.

Abstract. The standard ICP algorithm is a mainstream of 3D point cloud registration technique, which can establish effectively correct corresponding point set. An improved ICP algorithm based on inflection point is proposed. Our algorithm doesn't require the measured object having obvious features. As feature point, inflection point is easy to be obtained. Because not all of the data points are involved with, the amount of corresponding points is reduced. The experiment results show that our algorithm is more effective than other similar algorithms. Especially for large-scale data points, the algorithm has more advantages.

Introduction

3D point cloud registration technique [1] has been researching as one of hotspots and difficulties in the fields of computer vision, pattern recognition and surface quality detection etc. in which the key of registration techniques is to obtain coordinate transformation parameters R (rotation matrix) and T (translation vector). A common method of point cloud registration applied commonly at home and abroad is the standard Iterative Closest Point (ICP) algorithm [2]. ICP is a surface matching algorithm, mainly based on Point Set to Point Set (PSTPS). It can solve the problem of free-form surface registration, considered as a dominant algorithm of 3D object registration based on geometric models. In essence, ICP algorithm is mostly matched with least squares method. It carries out repeatedly the process from identifying the corresponding point set to calculating the optimal rigid transformation, until the best match with some convergence criteria will be achieved. Its purpose is to find the transformation of rotation matrix R and translation vector T between the target point set and reference point set, in order to get the most optimal matched transformation under some criteria. In this paper, six stages [3] of ICP proposed by Rusinkiewicz etc. and various algorithms improved are analyzed and compared. In order to solve the problem of temporal redundancy, the ICP algorithm was divided into four stages: (1) collect the data point set M and model point set N; (2) find feature points in the model point set N; (3) calculate the nearest point; (4) solve coordinate transformation. With four stages as a main line and in search of feature point set as center, some ideas and key techniques of ICP algorithms about feature point improvement are researched systematically and an improved ICP algorithm based on inflection point feature is proposed. The experimental result shows that the proposed algorithm can effectively improve the efficiency and accuracy of registration algorithm.

ICP algorithm and its improvement

ICP algorithm process. Suppose there are two point set groups, each containing n coordinate in the 3D space R^3, the data points set M={ m_i, i=1,2,…,k } and the model points set N={ n_i, i=1,2,…,l }. Set rotation transformation vector as a unit quaternion q_R= $[q0\ q1\ q2\ q3]^T$ and $q_0 \geq 0$, $q_0^2+q_1^2+q_2^2+q_3^2=1$, so the 3×3 rotation matrix R (q_R) can be obtained. Provided translation transformation vector q_T= $[q4q5q6]_T$, then the fully coordinate transformation vector q= $[q_R \mid q_T]^T$ can be obtained. Then the problem of optimal coordinate vector transformation between two point sets can be converted into attaining q to make $\mathrm{f}(q)=\frac{1}{N}\sum_{i=1}^{N_n}\|m_i-R(q_R)p_i-q_r\|^2$ minimum.

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The process of the standard ICP algorithm is as follows:

1 Obtain the corresponding point sets M and N;

2 Solve the center of gravity of the data point set M and model point set N respectively;

3 Construct covariance matrixes $\sum p, x$ with point set M and N;

4 Construct symmetric 4×4 matrix $Q(\sum p, x)$ with covariance matrix;

5Calculate all eigenvalues and feature vector of $Q(\sum p, x)$, the biggest feature vector corresponding with eigenvalue is the best rotation vector $q_R=[q_0q_1q_2q_3]^T$, the best translation vector q_T;

6 Obtain the fully coordinate transformation vector $q= [QR \mid q_T]^T= [q_0q_1q_2q_3q_4q_5q_6]^T$ and minimum mean square error $d_{ms} = f(q)$;

7 The end.

While the standard ICP algorithm can meet the accuracy requirements of point set registration, but there exists some problems in the design of algorithm itself, in that it makes the actual situations too realistic. In ICP algorithm, to obtain the closest point, it is necessary to compare each point in data point set M with the corresponding point in model point set N. But if two point sets are very large, it will take so much time that the speed of registration is very slow. It takes time O (N_MN_N) and it is tended to fall into seeking the local optimal solution. While scanning usually, it is difficult to get a full match between two point sets. Therefore it needs to be improved to enhance calculation efficiency.

ICP algorithm based on some feature points. In the standard ICP algorithm, to compensate for this deficiency, the most time-consuming is step (5) when calculating the nearest point. Some improved ICP algorithms based on the feature points have widely applied. Feature points [4] mainly refer to the points that have a key role of all data point sets, In general distribution in the intersection line between the curved surface and the boundary of the surface. At different visual angle, the geometric characteristics of the measured object surface in the same location should remain unchanged. Geometric features such as curvature, normal vector, etc. commonly are used as a condition of constraint to establish the corresponding points at a higher accuracy. Recently many improved ICP algorithms both at home and abroad are studied and analyzed by extracting certain characteristic from the free surface so as to determine the appropriate corresponding points based on these characteristics to ensure the accuracy of matching.

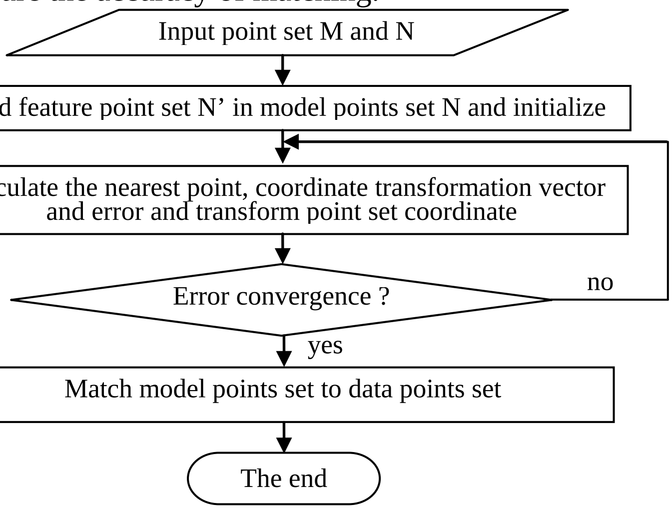


Fig.1 the improved ICP algorithm based on feature point

In reference [5,6], an algorithm of ICCP (Iterative Closest Compatible Point) was proposed, which used the curvature and angle between the normal vectors of the candidate corresponding points to determine whether feature points or not; In reference[7],Guehing used the distance from the candidate corresponding point pair (p,q) in combination with normal vector to determine the reliability. When point pair (p, q) meet $\|p-q\|<t_d$ and $n_p \cdot n_q>t_\alpha$ conditions, it was a correct corresponding point and was also considered to be a feature point. Wherein t_d, t_a were presupposed as threshold values and n was a normal vector; In reference [8], Sharp proposed an algorithm of ICPIF (Iterative Closest Points using Invariant Features), using Euclidean space invariants (curvature, moment invariants, etc.) of the measured object, this improved algorithm can greatly enhance the efficiency of establishing the corresponding point pairs; In reference[9], Bae etc. proposed an algorithm of GP-ICPR (Geometric Primitive ICP with the RANSAC), using the angle between one point on surface and normal vectors of its corresponding point, also including its curvature change, to establish point pairs. The process of some improved ICP algorithm based on these feature points is shown in Fig.1. By searching for feature point set in the model point set N, these algorithms can reduce the scale of the matching point cloud and time of finding the nearest corresponding point in the data point set M.

However, these algorithms above spent so much time on extracting feature values, especially when the surface contained more point cloud data. These methods required the object measured having more obvious features and fail to be intuitive, to understand and extract easily. In this paper, the improved ICP algorithm based on inflection point is a method easy to extract surface features. As for the vast amounts of point cloud data, extracting inflection point can reduce the number of point pairs matched and minimize the calculation error. It also can reduce matching time and improve the efficiency of the algorithm.

ICP algorithm based on inflection point. In this paper, the inflection point is extracted as feature point, regarding angle change as judgment condition. Firstly, according to the feature of inflection point, looking for a number of feature values in model point set, then using a k-d tree to find the nearest point, the time and searching complexity of algorithm, with these steps, can be reduced to O(NN), thus to solve the problem of calculation efficiency of ICP algorithm. Especially for a large scale of data points, the ICP algorithm based inflection point has more obvious advantages on time efficiency. Comparing with other improved ICP algorithm based on feature point, the algorithm proposed in this paper doesn't require the object measured having obvious features and easy to obtain. The implementation process of ICP algorithm based on inflection is shown as the following data and model.

(1) Give two point sets in R^n, the data point set M={ m_i, I=1,2,…,k } and model point set N={n_i, I=1,2,…,l}. According to invariants of spatial features between two feature points, feature points can be found in the model point set N firstly.

(2) Look for feature point set N'={n_i', $n_i' \in$ N, I=1,2,…,n} in N. Regarding inflection point (it refers to the point that can change the curve direction upward or downward in mathematics) as feature point. If the function of curve has second derivative in the inflection point, then second derivative must be zero or doesn't exist. In this way, it may take a lot of time to solve the inflection point. In this paper, a simple and effective method is proposed and its process is as follows:

1 Use the model point set N in a certain direction (X-axis or Y-axis) and connect each point in sequence. To judge whether as an inflection point for each point need to know the coordinates of the point, former point and next point.

2 Suppose the coordinates of point A, B, C to be (x_1, y1), (x_2, y2), (x_3, y3). Whether B is evaluated as the inflection point, is determined by the angle change between line AB (the same as BC) and axis (X-axis or Y-axis), here X axis is chosen.

3 Calculate the angle β (0≤β≤π), which is the angle between the line AB and X-axis.

$$\beta = \arctan\left(\frac{y_2 - y_1}{x_2 - x_1}\right) + \theta\pi \tag{1}$$

$$\theta = \begin{cases} 0 & \text{if } y_2 - y_1 > 0, x_2 - x_1 > 0 \text{ or } y_2 - y_1 < 0, x_2 - x_1 < 0 \\ 1 & \text{if } y_2 - y_1 < 0, x_2 - x_1 > 0 \text{ or } y_2 - y_1 > 0, x_2 - x_1 < 0 \end{cases} \tag{2}$$

Calculate the angle γ (0≤γ≤π), which is the angle between the line BC and X-axis.

$$\gamma = \arctan\left(\frac{y_3 - y_2}{x_3 - x_2}\right) + \theta\pi \tag{3}$$

$$\theta = \begin{cases} 0 & \text{if } y_3 - y_2 > 0, x_3 - x_2 > 0 \text{ or } y_3 - y_2 < 0, x_3 - x_2 < 0 \\ 1 & \text{if } y_3 - y_2 < 0, x_3 - x_2 > 0 \text{ or } y_3 - y_2 > 0, x_3 - x_2 < 0 \end{cases} \tag{4}$$

4 Calculate the angle β and γ. If $0<\beta<\frac{\pi}{2}$ and $\frac{\pi}{2}<\gamma<\pi$, or $\frac{\pi}{2}<\beta<\pi$ and $0<\gamma<\frac{\pi}{2}$, B is namely the inflection point, otherwise, B is not. Continue step 1, until all the points in the N are searched to get the feature point set N'.

(3) Initialize $N_0^{'}=N'$, $q_0=[1,0,0,0,0,0,0]^T$, k=0. So q_0 is the initial rotation transformation vector, namely the initial unit quaternion.

(4) Find the closest point set R from M to N' with the k-d tree: $R_k = C\ (N_k^{'}, M)$.

(5) Calculate coordinate transformation vector and error: $(q_k,d_k) = Q(N_0^{'},R_k)$.

(6) Transform feature point set: $N_{k+1}^{'} = q_i\ (N_0^{'})$.

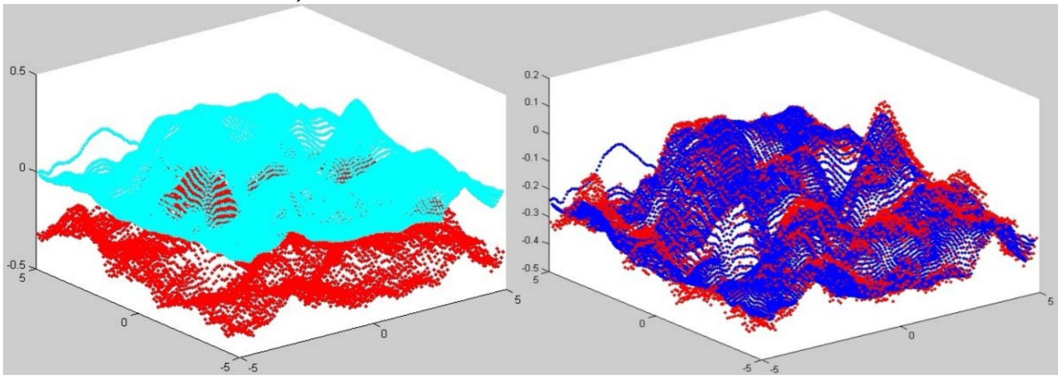
(7) Determine whether the error is converged, if $d_k-d_{k+1}<\tau$, τ is the set value and τ>0, then the condition is true, otherwise skip to step 5.

(8) Converge error to τ and make the target point cloud coordinates transformation: $N_{k+1}^{''} = q_k\ (N)$.

(9) The end.

Simulation experiments and results analysis

Simulation experiments. (1) Hardware environment: Pentium (R) processor, Dual-core CPU E5800 @ 3. 20 GHZ, 4.00 GB memory; (2) Software environment: Windows 7 operating system, the development tools is MATLAB, Auto CAD and 3 DMax.



(a) before matching (b) after matching

Fig.2 the data point set M and model point set N

By selecting 10000 data points as sample, the number of data point set M obtained after scanning and model point set N obtained after computer simulating all are 10000. The data point set M (represented by red dots) and model point set N (represented by light blue dots) before matching are shown in Fig.2 (a). Through simulation experiment, the proposed improved ICP algorithm in this paper can make two sets M (represented by red dots) and N (represented by deep blue dots) overlap together as much as possible. As shown in Fig.2 (b). The M and N are maintained at a coordinate system after matching, at the same time, the error between the corresponding points is much minimized. At last, the rotation matrix R and translation vector T are calculated as follows:

$$R=\begin{bmatrix}0.9982 & -0.0093 & 0.0594\\ 0.0087 & 0.9999 & 0.0097\\ -0.0595 & -0.0092 & 0.9982\end{bmatrix}\qquad \mathrm{T}=\begin{pmatrix}-0.0328 & 0.1340 & -0.9786\end{pmatrix}^T$$

Results analysis. As shown in table 1. We implement three comparative calculating strategies to compare with ICP algorithm including the standard ICP algorithm, an improved ICP algorithm [7], and the improved ICP algorithm based on inflection point proposed in this paper. Under the same scale of data, our algorithm takes less time than standard ICP algorithm on calculation speed. With the number of data points increasing, the standard ICP algorithm takes more and more time and grows at the rate of 5 times, in the same case, the growth rate of our algorithm on average time-consuming is very slow.

On the other hand, the registration time of point set is analyzed between our algorithm and the algorithm in reference [7]. Because extracting inflection point doesn't need extra time, the algorithm proposed in the paper has a larger advantage on registration time.

Table 1 the calculation speed of three ICP algorithms comparing

The scale of data points	The standard ICP algorithm Registration time(s)	An improved ICP algorithm Registration time (s)	The proposed ICP algorithm Registration time (s)
500	5.2344	5.2004	5.1025
1000	16.7243	14.6233	10.6545
3000	90.3432	60.7242	30.1232
5000	550.8767	345.2617	85.0232

Conclusion

Calculation speed is an important criterion to measure the performance of some ICP algorithms. According to the comparison of the standard ICP algorithm and other improved algorithms based on feature point, our algorithm based on inflection point is proposed in this paper. It can largely enhance efficiency of obtaining a closest point by reducing the number of points in model point set N and overcome the problem of making comparison with each point in data point set M. When the scales of two point sets are very large, in terms of calculation speed, the proposed algorithm is more efficient than existing similar algorithms.

Acknowledgments

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