Low-error star pattern recognition based on point cloud matching algorithm*

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Abstract: Aiming at the problem that the matching rate of traditional star map recognition methods is not high enough, this paper proposes a star map recognition method based on the ICP point cloud matching algorithm based on feature point extraction. Feature points are selected through the change of the local normal vector of the point cloud, and then used Common (ICP) algorithm to realize more accurate registration of point clouds. In order to further reduce the error rate of star map matching, an improved ICP algorithm based on feature points is used to accurately register the point cloud. Finally, the matching conditions of several star maps are obtained through MATLAB tool simulation and the matching rate error rate is calculated. Common ICP algorithm The minimum matching error of is 14.224, and the minimum matching error of the improved ICP algorithm based on feature points is 14.0715. Obviously, the star map matching error rate of the ICP algorithm based on feature points is lower, which also verifies the superiority of the improved ICP algorithm.

1. Introduction
Attitude measurement technology is an important technical support and guarantee for the precise orbit change of a spacecraft. Its core component, the star sensor, has the characteristics of autonomous observation, high measurement accuracy, reliable and stable operation, and is widely used in the attitude measurement of spacecraft in flight [1].

The core steps of star map recognition are image acquisition and preprocessing, feature point extraction and analysis, and point cloud data matching to identify star positions [2]. At present, many researchers have proposed related methods to solve the point cloud data registration. Lu Yinbei and others analyzed the curvature of the Hausdorff distance and the effective point pair according to the curvature characteristics of the selected point [3]; Jiang et al. used the clamp feet generated by calculating the normal vector of the feature point and the normal vector of the point in the similar field as the feature to point cloud registration research [4]; Basdogan et al. used the distance between the point and the center of gravity of the neighborhood as a feature to perform the point cloud registration process [5]; Besl uses the nearest iterative point (ICP) algorithm for point cloud registration and obtains a relatively accurate matching rate, but it must be satisfied that the distance between the two initial point clouds cannot be too large, otherwise the accurate matching rate cannot be obtained. error [6]. These traditional matching methods are mainly based on angular distance or its derived form for registration, which often has problems such as insufficient recognition accuracy and poor registration effect.

This paper adopts a low-error star pattern recognition method based on feature points and improved ICP point cloud matching algorithm. In the target point cloud, several feature points are extracted by the star point curvature feature, and then the obtained feature points are used to find the corresponding
closest point in the reference point cloud using the K-d tree method, so as to achieve the goal of reducing the star map matching error rate.

2. Principle analysis of matching algorithm

2.1 Feature point extraction based on point cloud normal vector

(1) Selection analysis of feature point set

To make the point cloud registration fast and effective, it is necessary to determine the feature point set at the beginning. When extracting feature points from all point cloud data, it is easy to observe the change of the normal vector of the point cloud. If you observe that the normal vector of the point changes smoothly in a local area, you can approximate that the area is flat, as shown in the figure (a); on the contrary, the obvious change of the normal vector in a local area indicates that the area fluctuates greatly, as shown in Figure 1(b).

![Figure 1: Schematic diagram of normal vector of point cloud in different regions](image)

2.2 Point cloud accurate matching

In this section, the nearest point iteration (ICP) algorithm is used for precise registration. To use the ICP algorithm, you must be familiar with the usage rules of the unit quaternion method in the algorithm.

2.3 Unit quaternion method

(1) The goal of point cloud registration is to find the coordinate transformation matrix of least squares approximation. The unit quaternion method can get two point clouds corresponding to each other. If the target point cloud q corresponds to the reference point cloud x, then these two point clouds should meet the following conditions:

(a) $N_q$ is the number of points in the point cloud of q, and $N_x$ is the number of points in the point cloud x, which satisfies $N_p = N_x$.

(b) Any point $q_i$ in the point cloud q corresponds to $x_i$ with the same subscript in the point cloud.
x, and satisfies $\overline{q} = \overline{x}$. Assuming that the unit quaternion $\overline{P} = [p_0 p_1 p_2 p_3]^{T}$ is the vector of
the rotation transformation, $P_0 \geq 0$ and $P_0^2 + P_1^2 + P_2^2 + P_3^2 = 1$, the rotation matrix $R$ can be obtained $R(\overline{P})$. Set another translation transformation vector $\overline{p} = [p_4 p_5 p_6]^{T}$, calculate the complete coordinate transformation vector $(\overline{P}) = [(\overline{P})^{T}]^{T}$. Since the transformation of $\overline{P}$ is equivalent to the optimal coordinate transformation of the corresponding point cloud space, the problem of the optimal coordinate transformation in the point cloud space can be solved by only the minimum value of the function of formula (3)\(^{[12]}\).

$$f(\overline{P}) = \frac{1}{N_q} \sum_{i=1}^{N_q} \|X_i - R(\overline{P})q_i - \overline{P}\|^2$$

The ICP algorithm can also be regarded as a registration method optimized and improved on the basis of the least square method.

### 2.4 Accurate registration of point cloud with improved algorithm

The time cost corresponding to the time consumption in the ICP algorithm is $O(N_q N_x)$, and it takes more time to process actual measurements with a large amount of data. On the basis of ensuring the registration accuracy, the time cost needs to be reduced to $O(N_q)$ as much as possible, then it can be applied to actual measurement engineering projects. The reason why the ICP algorithm takes a long time is that the nearest point set algorithm takes more time and the efficiency of processing data is relatively low. Therefore, this section will use the ICP algorithm based on feature point extraction to seek to improve the calculation efficiency of the traditional ICP algorithm. In the execution process, several feature points are extracted from the target point cloud through star point curvature feature recognition, and then the obtained feature points are searched for the corresponding closest point in the reference point cloud by K-d tree\(^{[13]}\), so as to reduce the time cost to the purpose of $O(\log N_x)$.

The algorithm flow is as follows:

1. First take the target point cloud Q (containing $N_q$ points) and the reference point cloud X (containing $N_x$ points);
2. Search for n feature points (n is a constant, such as n=1000) in the Q point cloud based on the curvature feature of the point, and take the feature point set $mathrm{F}$; initialization: $F_0 = F$, $q_0 = [1,0,0,0,0,0,0]^T$, $k=0$;
3. F is the closest point Y in the X point cloud: $Y_k = C(F_k, X)$ is searched by the method of k-d tree.
4. Find the coordinate transformation vector and error: $(q_k, d_k) = Q(F_0, Y_k)$;
5. Perform coordinate transformation of feature point set: $F_{k+1} = q_k(F_0)$;
6. If $d_k < \tau$, $\tau$ is the hypothetical value and satisfies $\tau > 0$, it can be considered as convergent and enter the next step. Otherwise, skip back to step 3;
7. Satisfying the condition that the error converges to $\tau$, the coordinate transformation of the corresponding target point cloud is $P' = q_k(P)$;
8. End.

### 3. Model establishment

#### 3.1 Registration model

Assuming that there are two point clouds in different three-dimensional coordinate systems, a rigid transformation matrix can be used to make the intersection area between them completely overlap, where the Z axis is the axis of rotation. By combining the two-dimensional rotation formula and the rotation law, a three-dimensional rotation transformation matrix can be obtained. When given in a right-handed coordinate system, the positive direction of the coordinate system rotation is the right-handed spiral direction, which can also be regarded as the direction of the positive semi-axis of the coordinate axis as viewed from the origin, counterclockwise is the opposite. The following formula (4) two angle sum difference formula, formula (5) is a two-dimensional coordinate rotation derivation formula:
\[
\begin{align*}
\sin(\alpha + \beta) &= \sin \alpha \cos \beta + \cos \alpha \sin \beta \\
\sin(\alpha - \beta) &= \sin \alpha \cos \beta - \cos \alpha \sin \beta \\
\cos(\alpha + \beta) &= \cos \alpha \cos \beta - \sin \alpha \sin \beta \\
\cos(\alpha - \beta) &= \cos \alpha \cos \beta + \sin \alpha \sin \beta
\end{align*}
\]

(4)

Around the origin of the coordinates, rotate a certain angle \( \rho \) with a radius of \( r \), as shown in Figure 2 below, the point \((x,y)\) is rotated counterclockwise through \( \alpha \) transformation to obtain \((x',y')\), known rotation angle \( \alpha \) and point \((x,y)\) coordinates, calculate point \((x',y')(x',y')\).

\[
\begin{align*}
x' &= r \cos(\alpha + \beta) = r \cos(\alpha) \cos(\beta) - r \sin(\alpha) \sin(\beta) = x \cos(\alpha) - y \sin(\alpha) \\
y' &= r \sin(\alpha + \beta) = r \sin(\alpha) \cos(\beta) + r \cos(\alpha) \sin(\beta) = x \sin(\alpha) + y \cos(\alpha)
\end{align*}
\]

[\(x'y'] = [\cos(\alpha) \sin(\alpha) - \sin(\alpha) \cos(\alpha)]
\]

(5)

The general rotation matrix \( R \) as shown in formula (6):

\[
R = R_z(\beta) R_y(\alpha) R_x(\theta) R = R_z(\beta) R_y(\alpha) R_x(\theta)
\]

(6)

The rotation process of the rotation matrix here first rotates the angle \( \theta \) around the x axis, then rotates the angle \( \alpha \) around the y axis, and finally rotates the angle \( \beta \) around the z axis.

Let \( Q_i, i = 1,2,3 \) represent the first point set, and \( P_i, i = 1,2,3 \) represent the second point set. As long as the value \( E \) of the objective function reaches the minimum, it can be regarded that the two point clouds have been aligned.

\[
\min E = \sum_i l \ln | |Q_i - (P_i \cdot R + T)||^2
\]

(7)

Among them, the rotation matrix \( R \) and the translation matrix \( T \) are the rotation parameters and translation parameters that need to be set between the point clouds to be registered. The optimal choice of these two parameters can satisfy a certain measurement rule between the two point clouds. Best match under.

4. Experimental simulation results

Input the star catalog data through the matlab simulation tool, read all the star map position information in the star catalog, and then perform point cloud matching. Figures 3 and 4 are the simulation results of the four star maps and the original star catalog. (The red circle in the figure represents the original data position, the blue solid ball represents the matching position of the ordinary ICP algorithm, and the green triangle is the matching position of the improved ICP algorithm)
Figure 3. Star map 1 and star map 2 star position matching map

The matlab command window outputs the simulation result data corresponding to Star Chart 1 and Star Chart 2:

General ICP registration Results: file1 for 1700 1384 2040 2655 3215 3711 4130 4466 4710 4858 4908 4858 4708 4463 The error is 16.7898
General ICP registration results: file2 for 4130 4575 4837 4906 4780 4463 The error is 15.2832
Improve ICP registration results: file1 for 1700 1384 2040 2655 3215 3711 4130 4466 4710 4858 4908 4858 4708 4463 The error is 16.4336
Improve ICP registration results: file2 for 4130 4575 4837 4906 4780 4463 The error is 15.2832

The matching error rate of Star Chart 1 common ICP algorithm is 16.7898, and that of improved ICP matching error rate is 16.4336.

The matching error rate of Star Chart 2 common ICP algorithm is 15.2832, and the matching error rate of improved ICP is 14.974.

Figure 4. Star position matching map of Star Chart 3 and Star Chart 4

The matlab command window outputs the simulation result data corresponding to Star Chart 3 and Star Chart 4:

General ICP registration Results: file3 for 4463 2245 934 3713 4901 3990 The error is 14.224
General ICP registration Results: file4 for 693 1510 3406 4611 4879 4156 The error is 18.3323
Improve ICP registration results: file3 for 4463 2245 934 3713 3990 The error is 14.0715
Improve ICP registration results: file4 for 693 1510 3406 4611 4879 4156 The error is 17.3623

The matching error rate of Star Chart 3 common ICP algorithm is 14.224, and that of improved ICP matching error rate is 14.0715.

The matching error rate of Star Chart 4 common ICP algorithm is 18.3323, and that of improved ICP matching error rate is 17.3623.

According to the experimental data and simulation diagram, it can be seen that the improved ICP algorithm has lower matching error rate and better matching effect than the ordinary ICP algorithm.

5. Conclusion

In this paper, an improved ICP point cloud matching algorithm based on feature points is used to effectively reduce the error rate of star map matching. Through simulation graph and simulation data analysis, the point cloud matching effect of four star graphs can be observed, and then the error rate of each star graph matching can be calculated; The matching error rate of the ordinary ICP algorithm and
the improved ICP algorithm are both in the range of 10-20; finally, comparing the star map simulation data, the lowest matching error of the ordinary ICP is 14.224, and the improved ICP algorithm based on feature points The minimum matching error is 14.0715. The matching error rate of the obviously improved ICP algorithm is lower, which also verifies the superiority of the improved algorithm.

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