3D reconstruction method of inner surface of pipeline

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Abstract. With the rapid development of China, there is a huge demand for PE pipelines. At present, the detection methods in pipeline production are mainly manual sampling testing and ultrasonic testing, which cannot display the internal surface characteristics of the pipeline comprehensively and visually, so as to facilitate the subsequent non-destructive testing. To solve this problem, this paper proposes a method to capture the three-dimensional feature data in the pipe with a depth camera, and transmit the collected point cloud data into PC for processing, identification and reconstruction, so as to realize the non-destructive testing of the inner surface of PE pipe.

1. Introduction
PE pipeline, as a kind of engineering pipeline, plays an important role in water engineering and building engineering. Compared with traditional metal pipe and cement pipe, it has the advantages of environmental protection and strong corrosion resistance. At present, the main testing methods for plastic pipe production are manual sampling testing and ultrasonic testing. Due to the heavy workload and low efficiency of manual sampling inspection, it is impossible to realize the all-sided inspection of all pipes. The ultrasonic detection precision is high, but it is not able to carry out a comprehensive visual display of the internal surface feature of pipelines, and the equipment cost is huge. In addition, people mastering ultrasonic theoretical knowledge are needed to monitor the production process.

2. 3D reconstruction process
The 3D reconstruction process after the depth camera collects the point cloud data includes Pre-treatment and Reconstruction. The Pre-treatment is to optimize the original point cloud data, eliminate useless and wrong information, and improve the processing efficiency, including registration, down-sampling, normal vector calculation, filtering. The Reconstruction is a process of three-dimensional reconstruction based on pre-processed point cloud data, including slice and surface reconstruction. This process is shown in Figure 1.
2.1. Pre-treatment

2.1.1. Down-sampling
The depth camera captures a large amount of point cloud data. Therefore, this method calls Voxel filter in PCL to subsample depth image to reduce point cloud data and speed up CPU processing. The method creates a 3D voxel grid based on the input point cloud, then calculates the center of gravity of each voxel, and replaces all points in the voxel with the center of gravity.

2.1.2. Registering
The camera generates two point cloud images. Similar clouds need registration, that is, the rotation and translation matrix between two point cloud images can be expressed as the following equation:

\[ P_s = R \cdot P_t + T \]  

Where \( P_t \) is a sampling point cloud, \( P_s \) is a target point cloud, \( R \) is a rotation matrix, \( T \) is a translation matrix.

The initial position and pose of the two point cloud images captured by depth camera may not completely coincide. If the distance is too far, the registration speed of the traditional ICP algorithm is slow, which cannot meet the requirements of the fast reconstruction of point cloud. NDT algorithm can get the high speed and low accuracy registration. Therefore, NDT algorithm is used for coarse registration to obtain conversion parameters, and ICP algorithm is used for precise registration of point cloud.

2.1.3. Normal vector calculation
The normal vector corresponding to each point cloud can be calculated to facilitate the denoising by bilateral filtering. The normal vector of a single depth point is only related to the spatial distribution of its neighbourhood points and does not change with the motion of the rigid body. In this paper, the local surface fitting method is adopted to solve the normal vector by the least square fitting estimation of the neighbourhood point, so that the dot product and absolute value of the neighbourhood point vector and the target point normal vector are as small as possible \[^1\].
2.1.4. Filtering and noise reduction
Because of the camera itself and the influence of the surrounding environment, the point cloud data collected by the camera often contain a lot of noise, outliers and voids, which will lead to the loss of characteristic information of the collected point cloud data and increase the error of 3D reconstruction. Therefore, it is necessary to design appropriate filters to repair it.

2.1.4.1 Remove outliers
Through filter is used to set the threshold to eliminate the highly discrete points in the point cloud. Then a statistical filter is used to analyze the neighbourhood of each point and calculate its average distance to all neighbouring points. Assume that the distance between the points obtained presents a Gaussian distribution, and its shape is determined by the mean value and standard deviation, as shown in the following equation:

$$
\mu = \frac{1}{nk} \sum_{i=1}^{m} \sum_{j=1}^{k} d_{ij}, \sigma = \sqrt{\frac{1}{nk} \sum_{i=1}^{m} \sum_{j=1}^{k} (d_{ij} - \mu)^2}
$$

Points whose mean distance is outside the standard range (defined by the global mean distance and variance) can be defined as outliers and removed from the data, i.e.:

$$
\sum_{j=1}^{k} d_{ij} > \mu + 3\sigma or \sum_{j=1}^{k} d_{ij} < \mu - 3\sigma
$$

2.1.4.2 Denoising
In this process, a bilateral filter is adopted to correct the position of the current sampling point by searching the weighted average value and root mean square error of neighbourhood points, so as to remove the noise, obtain the smoothing effect and maintain the edge characteristics\cite{2}.

2.2 Reconstitution

2.2.1 Slicing
Before the reconstruction of the surface, the point cloud should be sliced. The point cloud on the inner surface of the cylindrical pipe should be divided into small cylindrical point clouds, and then the surface should be fitted separately. The essence of point cloud slice is: a series of uniformly spaced planes and cylindrical points are clustered for intersection operation. The point cloud will fall into the neighbourhood with a certain thickness between the planes, and the intersecting points will be extracted. Then, the adjacent points of plane intersection are connected in series with virtual line segments, and the set obtained is the set of section points\cite{3}.

2.2.2 Surface reconstruction
In this paper, Poisson reconstruction algorithm is used to achieve smooth surface reconstruction. The core idea is that the point cloud represents the position of the inner wall of the pipeline, and its normal vector represents the internal and external directions. By implicitly fitting an indicator function derived from an object, an estimation of a smooth surface can be obtained\cite{4}.

3 Experimental analysis
The software environment used in the experiment in this paper is Visual Studio 2019, which runs on a Core i7-7500CPU, 16GB memory and 64-bit Win 10 operating system. In order to obtain the real point cloud model, this paper used Orbbec Deeyea camera to obtain two point clouds (Cloud One and Cloud Two) at the same position on the inner wall of the pipeline, as shown in Figure 2 and Figure 3. In order to present a complete reconstruction process of the inner surface of cylindrical pipe, a cylindrical pipe model was simulated by CAD software, which was converted into the cloud of disordered arrangement (Cloud Three) as an experimental model, as shown in Figure 4.
3.1 Down-sampling
All point cloud data collected are high-density point cloud data, with data points above 10,000. According to the requirements of the registration algorithm, the original point cloud was first sampled under voxel. Figure 5 shows the iterative estimation results of the edge length of point voxel in this paper.

Set the voxel side length as 5mm, create voxel grid for the original point cloud, and then conduct down-sampling. Figure 6 shows the images before and after voxelization of Cloud One.

3.2 Registration
In this paper, we call PCL point cloud library, register through NDT and ICP algorithm provided by IterativeClosestPoint class. Use above method to solve the optimal rotation and translation matrix.

At the first, NDT coarse registration was carried out. The maximum search length was set as 500, the grid resolution as $6\times10\times10$, the minimum conversion difference as 0.01, and the maximum number of iterations as 50. Finally, the coarse registration result was shown in Figure 7, its Euclidean degree of polymerization was 0.027381.
The next step is ICP precise registration. The minimum conversion difference was set as 0.01, and the maximum number of iterations was 100. Figure 8 shows the ICP registration renderings, in which the green point cloud is the origin cloud (Cloud Two), the red point cloud is the target point cloud (Cloud One), and the blue point cloud is the point cloud after ICP registration. The Euclidean degree of polymerization of the registration result was 2.47797e-05, presenting a high-precision registration.

3.3 Normal vector calculation
The point cloud model is analyzed by principal component analysis. By traversing the adjacent points, the covariance matrix is calculated, and the normal vector direction is finally obtained. Figure 9 shows the result of normal vector estimation.

3.4 Filtering and noise reduction
Statistical filter is used to remove outliers and set the number of adjacent points as 50, the threshold value of standard deviation as 1.0. The effect before and after filtering is shown in Figure 10:

Then, the point cloud coordinates and laser reflection intensity are input into the bilateral filter to smooth the point cloud boundary accurately.
3.5 Reconstitution
In order to present a complete reconstruction process of the inner surface of cylindrical pipe, cylindrical Cloud Three was used as the model.

The first step was cylindrical fitting for the model by RANSAC algorithm. After cylindrically fitting the point cloud to obtain cylindrical axis vectors, point cloud slices was obtained through cutting and projection. Figure 11 shows the projection of point cloud slice.

Finally, the point cloud containing normal vector data is used for Poisson reconstruction, and the model with surface triangular grid is obtained, as shown in Figure 12.

![Figure 11 Point cloud projection diagram](image1.png)

![Figure 12 Rendering of surface reconstruction](image2.png)

4 Conclusion
This paper proposes a reconstruction method of pipeline inner surface based on 3D point cloud processing, including registration, down-sampling, normal vector calculation, filtering, slicing, surface reconstruction. The scheme can effectively reconstruct the inner surface of PE pipeline and is helpful for non-destructive testing in pipeline production.

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