Curved path planning based on 3D vision water immersion ultrasonic nondestructive testing

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Abstract. Compared with traditional 2D image processing, 3D point cloud processing has become a hot technology in the industry, but there are few researches applied to nondestructive testing of curved workpieces. This article aims at the non-destructive testing of curved workpieces, using 3D point cloud and robotic arm for water immersion ultrasonic non-destructive testing. Aiming at the 3D point cloud with many outliers, using the commonly used filter in two-dimensional images-the guide filter, the algorithm is improved and used for the filtering and downsampling of the 3D point cloud, and the adjustment of the curved surface workpiece and the robot arm's pose is introduced. Finally, the workpiece was scanned by a robotic arm with a water immersion ultrasonic nondestructive testing system to prove the feasibility of the experiment and improve the detection efficiency of traditional nondestructive testing technology.

1. Introduction

Industrial environments do not detect a large number of scanning platforms using water immersion scanning. Ultrasonic testing is widely used in industrial testing due to its ability to absorb and strong sound energy, and its advantages such as good quality, strong ability, and low harm to the human body. Point by point and line by line scanning is used for scanning, so the imaging speed is slow, and the automatic detection of complex targets can be continued to detect the realization of the target equipment. In most cases, manual detection can still be used to accurately obtain effective detection.[1] Both guaranteed. Because the 3D structured light technology does not need to use a very suitable time and space delay method to solve the problem of the complexity and robustness of the two-dimensional image matching algorithm.[2] Therefore, the article is based on the 3D surface structured light camera data measuring instrument, combined with the acquisition of the target point cloud, the movement of the manipulator, and the water loss avoidance detection experiment. This will prove the efficiency and feasibility of integrating 3D vision into the non-destructive testing industry in this experiment, and emphasizes the importance of the vision module in the industrial field.
2. Curved workpiece path planning
When performing non-destructive testing of curved workpieces, because the curvature of the workpiece surface, the ultrasonic beam will enter the workpiece surface at a certain angle.[3] Taking into account the influence of water immersion ultrasonic refraction and diffraction, the echo energy at the detection defect position will be smaller and the curvature will be lower. At large, there is almost no echo. Therefore, it is necessary to enter the sound beam perpendicularly into the workpiece to make the echo energy the strongest. Therefore, it is necessary to keep the sound beam direction of the ultrasonic transducer consistent with the normal direction of the workpiece at all times.

2.1. Point cloud preprocessing
Due to some factors in the tiny environment, a group of people gather together information, the overall point of the destination point cloud image appears, and it is necessary to filter out points and noise. In addition, the scanning device acquires the point cloud information. Due to the large amount of data, the dense information points, and the ignorance of their storage, transmission and calculation, it is necessary to down-sample this information.

2.1.1. Point cloud downsampling
The article will make the voxel grid filter downsample the point cloud. It creates a three-dimensional voxel grid coordinate system from the original point cloud data.[4] Then, in each voxel, other points in the voxel are displayed approximately by all the centers of gravity in the voxel, so that all points in the voxel are finally displayed by one Center of gravity said. For the point cloud obtained after all voxel processing, this method is slower than the voxel center approximation method, but it has higher accuracy for the surface corresponding to the sampling point.

2.1.2. Point cloud filtering
Common point cloud filtering algorithms in the industry: space cell method, voxel filtering, radius filtering, Laplace smoothing algorithm, etc. However, each algorithm has its certain of limitations, for example, voxel filtering is more approximated by voxel center The method is slower and the calculation efficiency is lower. Laplace smoothing algorithm will cause edge loss and overall size reduction. Both the radius of the circle and the number of points in the circle in the radius filter need to be manually specified. Therefore, we weigh the pros and cons of various filtering algorithms. In order to improve the computational efficiency and filtering quality, this paper uses the classic filtering algorithm based on traditional images—guided filters to improve it and adapt it to the filtering requirements of 3D point clouds.

After preprocessing, 33236 point cloud data are obtained, as shown in Figure 1. It can be seen from the figure that the length (X axis) of the surface of the workpiece to be inspected is 250mm, the width (Y axis) is 90mm, and the height (Z axis) is 57mm. Figure 1 is the point cloud image after point cloud downsampling and filtering.

2.2. Point cloud slice

2.2.1. Point cloud normal vector estimation
The detection path is a set consisting of a series of sliced data points called the sampling point set Q, promptly:
\[ Q = \{ Q_i(x_j, y_i, z_i), i = 1, 2, \ldots, t \} \]  
\hspace{1cm} (1)

Where \( x_j \) is the X coordinate of the slice plane of the \( j \)-th layer, and \( i \) represents the number of the sampling point on the slice plane of the layer [5].

In this paper, the normal vector of the tangent plane is estimated by using the triangular topological structure of the scattered data, and the normal vector of the relevant triangle of the point is obtained, and the direction of the directed triangle is used to determine the direction of the normal vector. There are \( a \) points \( Q_j \) (\( j = 1, 2, \ldots, m \)) around the sampling point \( P_i \), forming \( a \) triangles. The unit normal vector \( n_j \) is composed of \( P_i, Q_j, Q_{j+1} \). Figure 2 shows the processed workpiece point cloud method vector information.

\[ n_j = \frac{(Q_j - P_i) \times (Q_{j+1} - P_i)}{\| (Q_j - P_i) \times (Q_{j+1} - P_i) \|} \]  
\hspace{1cm} (2)

Figure 2. Workpiece point cloud method vector information

2.2.2. Detection probe track point acquisition

According to the working requirements of the detection probe, the vertical distance between the probe and the surface of the curved workpiece is \( h_i \), and the running trajectory parameters of the spray gun can be obtained using the following offset algorithm:

(1) For the point \( P_i \), offset the distance \( h_i \) along the normal vector \( n_i \), and get the point, the offset point \( O_i \) of \( P_i \). The mathematical expression is:

\[ O_i = Q_i + H \frac{N_i}{\| N_i \|} \]  
\hspace{1cm} (3)

Point \( O_i \) contains two information: coordinate value and unit normal vector \( \frac{N_i}{\| N_i \|} \). In addition, the coordinate value of the probe at \( O_i \) is opposite to the direction of \( n_i \).

(2) Using the same method to traverse all the points in the sampling point set \( Q \), the offset point set \( O \) can be obtained. Therefore, the information contained in the entire point set \( O \) represents the trajectory parameters of the probe on the running surface during the detection process. Figure 3 shows the final point cloud slice path diagram.

Figure 3. Point cloud slice path

3. Experimental verification

The article is verified by a robotic water immersion ultrasonic inspection system based on a 3D point
cloud. This system controls the movement of the mechanical arm on the surface of the curved workpiece, synchronously completes the ultrasonic inspection, and realizes the C-scan imaging.

3.1. System control process

The overall scheme of the 3D vision robotic arm water immersion production ultrasonic inspection system is shown in Figure 4. The entire inspection system is composed of vision, robotic arms, and inspection modules. The organic combination of the three forms the core of the new non-destructive inspection system. The software system mainly includes manipulator scanning movement trajectory planning software and non-destructive testing result display software.

![Figure 4. 3D Vision Robotic Arm Water Immersion Production Ultrasonic Inspection System](image)

3.2. Experimental results

Figure 5 is the curved surface workpiece to be inspected, and Figure 6 is the imaging diagram of the workpiece in the water immersion ultrasonic C-scanning instrument after inspection. From the scanning results, the defects detected are consistent with the surface defects of the original workpiece; in addition, it only takes 12 minutes to detect the workpiece. Compared with the traditional non-destructive testing equipment, the work efficiency is higher and the testing precision and accuracy are higher.

![Figure 5. Surface workpiece to be inspected](image)

![Figure 6. Image of water immersion ultrasound C-scan instrument](image)

4. Conclusion

Based on the shortcomings of the traditional C-scan non-destructive testing system, this paper proposes a non-destructive testing method based on 3D vision robotic arm. The traditional two-dimensional image filtering method-guided filter is improved to a method suitable for 3D point cloud filtering, and then point cloud is used. The slice forms the inspection path, and then the non-destructive inspection is
performed by the robotic arm. The system in this experiment can complete the detection of workpieces with a length of 20-100mm, and the maximum weight of the tested workpiece is 5kg. The defect detection ability can detect the diameter of 0.1mm. Flat-bottom hole defects and 0.1mm x 8mm groove defects. The thickness measurement range is 0.5-10mm, and the measurement accuracy is ±0.02mm. It successfully improved the shortcomings of traditional C-scan.

However, the use of 3D visual non-destructive testing has certain limitations. In locations with larger curvatures, the interface echo is small, which is not conducive to judgment; and the point cloud processing cannot avoid accuracy errors. The next step is to use point cloud reconstruction. Point cloud modeling to improve the efficiency and accuracy of surface planning.

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References
[1] Yusen Geng et al. A method of welding path planning of steel mesh based on point cloud for welding robot[J]. The International Journal of Advanced Manufacturing Technology, 2021,  : 1-15.
[2] Lei Yang et al. A novel system for off-line 3D seam extraction and path planning based on point cloud segmentation for arc welding robot[J]. Robotics and Computer-Integrated Manufacturing, 2020, 64
[3] Xiangfei Wang et al. Point cloud 3D parent surface reconstruction and weld seam feature extraction for robotic grinding path planning[J]. The International Journal of Advanced Manufacturing Technology, 2020, 107(2) : 827-841.
[4] Anadil Masood,Rooha Siddiqui,Michelle Pinto,Hira Rehman,Maqsood A. Khan. Tool Path Generation, for Complex Surface Machining, Using Point Cloud Data[J]. Procedia CIRP,2015,26.
[5] Chen W , Li X , Ge H , et al. Trajectory Planning for Spray Painting Robot Based on Point Cloud Slicing Technique[J]. Electronics, 2020, 9(6):908.
[6] Morozov, M., Pierce, S.G., MacLeod, C.N., Mineo, C., Summan, R. (2018) Off-line scan path planning for robotic NDT. Measurement, 122: 284-290.
[7] Lu, Z., Xu, C., Pan, Q., Zhao, X., Li, X. (2015) Inverse kinematic analysis and evaluation of a robot for non-destructive testing application. Journal of Robotics, 596327: 1-7.
[8] Yang, Z., Yong, Y . (2014) Boundary extraction based on point cloud slices. Computer Applications and Software. 31: 222-224.
[9] He X., Zhuo Y., Pang M. (2014) An algorithm for extracting hole-boundary from point clouds. Transactions of The Chinese Society of Agricultural Machinery. 45: 291-296.