On-Line 3D reconstruction based on laser scanning for robot machining of large complex components

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Abstract. The digital model is the foundation of intelligent manufacturing based on robot machining. In the intelligent manufacturing of large complex components in the fields of aerospace, energy equipment, shipbuilding, etc., it is often necessary to perform online 3D reconstruction of these large-sized components. In response to this demand, this paper designs a large-scale on-line 3D reconstruction system based on laser scanning principle. A laser scanner is used to generate the contour of the component accurately. Then, a series of contour sequences are generated by the movement perpendicular to the direction of the contour plane. These contour sequences are processed by algorithms to generate the 3D point cloud model of the large complex component. The results show that the system can generate the 3D point cloud model of large-scale complex components in an on-line manner and provide the basis for the detection of the components before machining and the machining planning in some cases.

1. Introduction
In recent years, there has been tremendous growth in smart manufacturing, and the degree of intelligence is getting higher and higher [1]. The demand for intelligent manufacturing of large components in the fields of aerospace, energy equipment, heavy machinery, shipbuilding and the like has increased remarkably. In robotic machining-based intelligent manufacturing, the digital model is particularly important for the planning of large-scale components, the pre-processing inspection after the components is installed, and the processing quality inspection after processing [2-3]. Under normal circumstances, the model of these components can be obtained by manual design, but even in the case of the existing design model and the corresponding processing plan, due to the large size of these components, the movement is difficult [4], after the components is installed, The detection often also need online access to these components of the 3D model and the existing design model matching positioning. In some cases, it is even difficult to obtain the existing design models. In this case, the processing planning and pre-processing inspection of the components are more dependent on acquiring the 3D models of the components online. Therefore, the research of on-line 3D reconstruction of these large components is of great significance for the intelligent manufacturing of large components in these industries.

At home and abroad, many researches have been done on online 3D reconstruction applied to industrial fields. Multi-view matching is a basic method of 3D reconstruction from 2D images. There are a large number of mature and reliable matching algorithms in computer vision and photogrammetry [5-8]. In order to overcome the sensitivity of 2D image acquisition to environmental
changes, active structural light sources are usually added to enhance the feature points of 2D images to reduce the requirements of the multi-view matching algorithm for images. There are already many commercial products using this principle to achieve, such as the famous Kinect-v1 [9], as well as a variety of high-precision 3D scanner at home and abroad are using this principle. The advantage of this method is the high precision. However, this method not only requires multi-angle and multi-position data acquisition, but also makes it difficult to design a common scanning method, and finally, the overall cost is also high. There is also a SFS (Shape from Shading) algorithm that reconstructs a 3D image from a single 2D image. The principle is to restore the relative height of each point on the surface or the normal direction of the surface. Such parameters, reconstruction of the object surface shape [10-11]. However, such methods are not suitable for large components with complex shapes. In recent years, the appearance of TOF (Time of Flight) area array camera, you can directly access the component's depth image, a typical commercial product Kinect-v2. This principle of the products are mostly used in mobile robot navigation and precision of some areas less demanding [12-13]. Still another type of basic 3D reconstruction method commonly used in the medical field is a contour-based 3D reconstruction method that reconstructs a 3D model by processing a sequence of spatially ordered contours. This method is often used in the industrial field. The sensors obtained from the contour lines have different principles and are mainly classified into structured light and TOF type. Which structured light is based on triangulation to obtain the outline of the principle, which has the advantages of high precision and is commonly used in the 3D inspection industry. But the disadvantage is that the field of view and the measurement distance are too small, the data acquisition frequency is lower. So 3D reconstruction system based on these sensors are difficult to meet the large size requirements. The TOF type acquires the contour by rotating a single point TOF sensor, which has the advantage of high scanning frequency and little influence on the external environment. In the mobile robot industry, this type of scanning sensor is often called a LIDAR, but 3D reconstruction based on LIDAR is mostly used for mobile robots or driverless navigation. The above studies are 3D reconstruction studies on the characteristics of their respective fields and provide important technical means and data foundation for their respective fields. But in the face of large-size complex components, or because of the need for a large amount of preparatory work or processing time is too long and difficult to meet the processing requirements of industrial-line beating online requirements; or because the measurement range is too small to meet the large size requirements. Or because of the need for more complex scanning methods difficult to form a common scanning scheme, and the limitations of the principle can not meet the mechanical and surface reflectance of the complexity of the components.

In this paper, aiming at the demand of intelligent system based on robotic machining, a large-size fast 3D reconstruction system based on laser scanning principle is designed. The contour of the component is scanned by multiple laser scanners and the contour sequence is generated by moving the scanning perpendicular to the contour plane, and then get the 3D point cloud model of the component through fast algorithm. For the components after the installation of the pending testing and processing to provide follow-up planning technology base.

2. System structure
The composition of a large-scale on-line 3D reconstruction system is shown in figure 1, which is composed of a workbench, a gantry and two laser scanning sensors and industrial robots fixed thereon. One workbench for placing the component, the height of 300mm, a width of 3000mm, the length can be extended according to operating conditions. The gantry is used to generate and scan the vertical direction of the laser scanning fan. Gantry width 4250mm, gantry lower end distance from the table 1900mm. Industrial robots mounted on gantries for subsequent machining. The laser scanning sensor calculates the distance by a single point laser pulse emitted by the receiver and the beam received by the receiver, and then through the phased array or mechanical rotation device to achieve full range measurement. The maximum scanning frequency of the laser scanner in this system is 500Hz, the angular resolution is 0.25 degree, the distance resolution is 1mm and the measuring distance is 700m
to 3000m. Measuring angle range of 70 degrees. Two were installed in the upper gantry at both ends, can produce complementary scan data.

![Figure 1. Large-scale online 3D reconstruction system diagram.](image)

3. Algorithm
The 3D reconstruction system needs to calibrate the contour sensor first, and then process the obtained contour sequence, and the data obtained from the multi-sensor fusion to generate the final 3D model of point cloud.

3.1. Scanner calibration
The sensor calibration in 3D reconstruction system generally correlates the sensor coordinate system with the measurement reference coordinate system through the known points on the standard template with the 3D coordinates, and then obtains the transformation matrix between the two coordinate systems [14-15]. The data obtained directly by the scanner is the distance value sampled by the rotation angle. Using a 3D vector \((\rho, \theta, x_s)\) under the cylindrical coordinates of the \(x\) axis of the scanner with the optical center of origin as the origin, the scanning plane as the radial plane, and the scanning rotation axis as the \(x\) axis, where \(\rho\) is the single point sampling distance and \(\theta\) is the single point sampling angle, \(x_s\) is the \(x\)-axis component of the sampling point, the value of the constant zero because the scanner scan range is a 2D sector. For the convenience of processing, a scanner is set up with the origin of the light emitted by the scanner as the origin, a \(z\)-axis direction in front of the scanner emission, a \(y\)-axis direction on the right of the scanner, and a Cartesian coordinate system of the \(x\)-axis of the scanning rotation axis. The acquired cylindrical coordinate system data can be transformed into the 3D vector \((x_s, y_s, z_s)\) by

\[
x_s = \rho \sin \theta, \quad y_s = \rho \cos \theta, \quad z_s = 0.
\]

After installation, the scanner and the reference coordinate system form a transfer matrix, denoted by the homogeneous matrix \(R_{sb}\). In the system designed in this paper, when installing the scanner, fine-tuning makes the scanner coordinate system parallel to each axis of the reference coordinate system, and only deflects in the movement direction of the gantry, that is, on the \(x\)-axis of the reference coordinate system. Therefore, the data vector in the scanner coordinate system and the data vector in the measurement reference coordinate system can be related by

\[
R_{sb} = \begin{bmatrix}
1 & 0 & 0 & x_0 \\
0 & \cos \gamma & \sin \gamma & y_0 \\
0 & -\sin \gamma & \cos \gamma & z_0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)
To solve the system of equations (2), it is necessary to know the precise data of the measured point in the reference coordinate system. And then the laser emitted by the scanner is a continuous line, it is not easy to confirm the measured points respectively in the scanner coordinate system and the reference coordinate system data. Therefore, this paper designed a 3D feature calibration for the production of markers. The principle shown in figure 2.

![Figure 2. Laser scanner calibration diagram.](image)

The reference coordinate values of the marker points A, B, and C can be obtained from the reference coordinate view function of the industrial robot. And then from the scanner data to find out because of the sudden changes in the profile of the points A, B, C scanner coordinates. Because the selected A, B, C mark points have the following characteristics: A and B have the same value on the z-axis and B and C have the same value on the y-axis, the calculation of simplified calculation of scanner deflection angle \( \gamma \) can be introduced into equation (3) Where \( y_A, z_A, y_B, z_B, y_C \) and \( z_C \) are the corresponding y-axis coordinates and z-axis coordinates of point A, point B and point C, respectively. Formula 3 is due to the choice of multiple markers and redundant calculation formula, can be obtained on average to obtain more accurate deflection value. Other values can be obtained according to the deflection value into equation (2) get:

\[
\gamma = \arctan\left(\frac{z_A - z_B}{y_A - y_B}\right)
\]

\[
\gamma = -\arctan\left(\frac{y_B - y_C}{z_B - z_C}\right)
\]

3.2. Data Processing and fusion

The data once collected by the scanner is transformed into m 3D vector \((x_b, y_b, z_b)\) sample points after being transformed by the reference coordinate transformation matrix \(R_{sb}\). Writing in matrix form can represent a section outline of the component at a certain moment. Suppose one of the contours is \(C_i\), then (4).

\[
C_i = \begin{bmatrix}
x_{b1}, x_{b2}, \ldots, x_{by}, \ldots, x_{bm} \\
y_{b1}, y_{b2}, \ldots, y_{by}, \ldots, y_{bm} \\
z_{b1}, z_{b2}, \ldots, z_{by}, \ldots, z_{bm}
\end{bmatrix}
\]

These contours are arranged in order of acquisition time to obtain an element of the n-dimensional vector matrix, with Q to represent this vector. Where \(n\) is the number of profiles collected, and the gantry moving the scanning speed \(v_{scan}\) and the distance \(d_{scan}\) and the scanner's scanning frequency \(f_{scan}\), as shown in equation (5):
\[ Q = \left( C_1, C_2, \ldots, C_i, \ldots, C_n \right), n = \frac{d_{\text{scan}} f_{\text{scan}}}{v_{\text{scan}}}; \]  

(5)

Since the value of \( n \) is generally large, there is an additional burden on the processing and storage of data, so the vector \( Q \) needs to be dimensionally reduced. The dimension of the new vector \( P \) is related to the accuracy of the 3D reconstruction point cloud. Let the dimension of a new vector \( P \) be \( k \), then \( Q \) can be decomposed into sub-vectors made up of \( k \) C's and the weighted sum of these sub-vectors gets the element \( C_i^p \) of the new vector \( P \). As shown in equation (6):

\[ P = \left( C_1^p, C_2^p, \ldots, C_i^p, \ldots, C_k^p \right) \]

\[ C_i^p = \frac{1}{\text{floor}(n/k)} \sum \left( C_{1+i(\text{floor}(n/k))}, C_{2+i(\text{floor}(n/k))}, \ldots, C_{j+i(\text{floor}(n/k))}, \ldots, C_{\text{floor}(n/k)+i(\text{floor}(n/k))} \right); \]

(6)

\( P \) here is a point cloud data generated by a laser scanner. Since both laser scanners of this system are calibrated, the two point cloud data \( P_R \) and \( P_L \) generated are under the reference coordinate system. This omits point cloud registration steps and time, the system processing speed can be further improved.

4. Experiment

In addition to the complexity of the industrial components embodied in the mechanical structure by the multi-surface structure, but also due to different materials caused by uneven optical reflectivity. This has caused difficulty for general 3D reconstruction. In order to verify the modeling effect of the 2D reconstruction system in this paper, we choose a truck wheel hub with a diameter of 600mm and a height of 300mm as the component. The hub is shown in figure 3a. The component is made of High-strength steel, Very uneven reflective surface. Set the scanning length to 1000mm and the scanning speed to 20mm/s, 40mm/s, 60mm/s, 80mm/s, 100mm/s respectively. The 3D point cloud generated after scanning is shown in figure 3b, figure 3c, figure 3d, figure 3e and figure 3f respectively. The maximum cross-section diameter of its point cloud model is shown in table 1. The error in the table represents the error of point cloud diameter, and the time represents the generation time of point cloud model. The difference of time will be analyzed later. The point cloud in the table corresponds to the letter in figure 3. Experiments show that with the increase of scanning speed, the overall accuracy of the model tends to decrease slightly. This is caused by a decrease in the number of profile acquisitions per unit length because of the fixed profile acquisition frequency. However, overall the accuracy of the model can be controlled within 3 mm at a scanning speed of 100 mm/s. This is for robotic pre-processing and design model positioning and matching can be satisfied.

![Figure 3](image-url)  

**Figure 3.** 3D reconstruction of truck hub. (a) is the wheel hub, (b-f) is the 3D point cloud generated at a scanning speed of 20mm/s, 40mm/s, 60mm/s, 80mm/s and 100mm/s respectively.

In addition, in order to verify the adaptability of 3D reconstruction system to the requirement of large size and on-line speed of the component, a water-cooling panel for boiler was scanned, which was 3100mm long, 400mm wide and 6mm high, as shown in figure 4a. Set the scanning speed to 100mm/s and the scanning length to 3500mm. The generated 3D point cloud after scanning is shown in figure 4b. Point cloud generation time is 38.3s (including scan time). Combined with table 1. point cloud generation time, the experimental results show that, in fact, the 3D reconstruction time of the
whole system consists of two parts: the time of data acquisition and the time of data processing. The time of data acquisition depends on the scan length and scan speed, which is related to the size of the component to be scanned. The data processing time is about 3s, the size of the component has less effect on it.

Table 1. The diameter and error of point cloud model at different scanning speeds.

|                | Hub | Point-Cloud b | Point-Cloud c | Point-Cloud d | Point-Cloud e | Point-Cloud f |
|----------------|-----|---------------|---------------|---------------|---------------|---------------|
| Diameter(mm)   | 600 | 600.7         | 601.2         | 602.5         | 602.1         | 602.6         |
| Error(mm)      | -   | 0.7           | 1.2           | 2.5           | 2.1           | 2.6           |
| Time(s)        | -   | 53            | 28            | 19            | 16            | 13            |

Figure 4. Part of the water-cooling physical(a) and three-dimensional point cloud(b).

In order to verify the 3D system's support for the robotic follow-up planning, a certain type of component with rib is scanned. The component with rib is 1000mm long, 1000mm wide and 120mm high, as shown in figure 5a. Figure 5b is a point cloud model generated after scanning. The obtained point cloud data is subjected to surface reconstruction to obtain a triangulation model. The model can be imported into the offline programming software for processing planning as shown in figure 5c, and can also be used for processing the same type of component Identify and match the template.

Figure 5. Component with rib(a) and their point cloud model(b) and the corresponding triangulation model can be used for off-line programming(c).
5. Conclusions

Robot machining-based intelligent manufacturing often requires the on-line 3D reconstruction of large and complex components. In this paper, based on laser scanning and contour line 3D reconstruction technology, a robot-based, non-contact large-scale on-line 3D reconstruction system is designed. The structure and working principle of 3D reconstruction system are introduced. The core algorithms used in the system are studied, including the calibration of the laser scanning profile sensor, the dimension reduction of contour sequence, and the generation of 3D point cloud. The experimental results show that the 3D reconstruction system in this paper can make fast online modeling of large and complex components, and provide a data foundation for pre-processing inspection and machining planning of the components that are intelligently manufactured. In addition, through the expansion of the gantry system, the system can reconstruct larger components and can be widely used in many fields.

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