Automatic high-precision measurement technology of special-shaped surface parts based on robot arms

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Abstract: In order to meet the requirements of large-scale, special-shaped surface, high-precision surface measurement of product parts, an automated, high-precision robot arm measurement system based on industrial robots is proposed. According to the D-H method, the relative posture conversion relationship between the robot arm and the elastic probe is discussed. In addition, on the premise of considering the contact deformation between the elastic probe and the measuring surface, the coordinate data of the measuring point is obtained based on the probe deformation model. At the same time, the accuracy calibration is performed by means of visual photogrammetry, and the validity of the coordinate measurement data of the profiled surface is guaranteed.

1. Introduction
With the continuous development of scientific progress and technological innovation, the structure and shape of mechanical products are becoming more and more complicated. Especially in the fields of aerospace, defense, weaponry and other manufacturing fields, the surface of parts and components presents the development direction of large-scale, special-shaped surface and high precision. At present, the degree of automation of online inspection of products is not high enough to match the accuracy and capabilities required for parts production. Accurately measuring and evaluating the three-dimensional topography of special-shaped parts and studying the surface geometric characteristics are of great significance for improving the quality of processed surfaces and product performance. The current machinery manufacturing industry is developing towards large-scale integration, automation, and intelligence. Therefore, the digital measurement and quality inspection technology of mechanical parts with high precision, high efficiency and adaptability to multiple profiled surfaces have become an important part of the flexible manufacturing system. At the same time, it is an indispensable technical tool for reverse engineering, product prototype data acquisition in digital manufacturing, and physical simulation experimental research\textsuperscript{[1]}.

The measuring principle of special-shaped surface can be basically divided into two categories: contact measurement and non-contact measurement. Contact measurement is represented by a coordinate measuring machine and an articulated measuring arm\textsuperscript{[2]}. The installation conditions and operation of the traditional three-coordinate measuring instrument are complicated, and the measurement efficiency and accuracy are highly relevant to the operator. In the mid-1990s, China introduced a portable manipulator coordinate measuring machine, which was favored by the market.
for its series of advantages, such as its light weight and large-scale measurement. Non-contact measurement is divided into reflection measurement: including laser measurement (such as hand-held 3D scanner, industrial robot scanning system[13]) and visual photogrammetry. While, penetrating layer-by-layer measurement includes ultrasonic measurement and industrial CT and MRI nuclear magnetic measurement. The non-contact measurement technology can realize the real-time online measurement of the three-dimensional shape of the irregular surface to a certain extent. However, when it performs high-precision measurement of the three-dimensional shape of curved parts with large surface shape, large curvature, and high reflection, the technical capabilities of non-contact measurement cannot meet the requirements.

As a series joint structure system, the multi-joint measuring manipulator based on industrial robot has the advantages of wide measuring space, flexible operation, mobile and portable, low environmental requirements, suitable for on-site measurement and online measurement[4]. It has been widely concerned by many researchers in the world for a long time. In order to effectively improve the measurement accuracy of the robot arm coordinate measuring machine, the following improvements are proposed in this paper: (1) The relevant error factors such as the force and deformation of the measuring probe are accurately identified; (2) Mathematical models such as the elastic probe and the local deformation of the test piece are established; (3) The measurement accuracy is more accurate based on the technical means of visual photography[5][6].

2. The composition and principle of the robot arm measurement system

The end effector of industrial robot has the characteristics of precise controllability and high degree of freedom of movement. Therefore, the coordinate measuring system has the advantages of large measuring range, convenient and flexible, high precision, and good environmental adaptability. In addition, it is also convenient to detect the parts of the work-piece that are not easily penetrated by the orthogonal coordinate measuring machine. The robot arm measurement system can be combined with assembly line production. It integrates automated data collection and data processing systems, and can provide real-time and intuitive data analysis results for users to use, rather than just independent measurement and inspection from the manufacturing process. The hardware system composition is shown in Figure 1 (Fig. 1).

First of all, install the parts with special surface to be measured on the measuring tool. Secondly, the movement of the robot arm is controlled by a preset program, so that the elastic probe installed at the end of the arm makes good contact with the surface of the object to be measured. Afterwards, the six-dimensional sensor transmits the data to the computer. At the same time, verify and correct the arm posture through the vision system to ensure the accuracy of the measurement.

According to the principle of robot kinematics, the joint rotation angle and the structural parameters of the measurement arm are obtained, and the spatial position of the probe contact point in
the measurement coordinate system is calculated by combining the probe elastic deformation model. It is worth noting that when the surface of the measuring component is too large to measure at one time, points can be set at different positions around the object, and the multi-station measurement method can be adopted to obtain the block point cloud data of each part of the object. Finally, the complete surface size of the object is obtained through the stitching process of the calibration data between the various stations[7].

3. Measurement Analysis Modeling of Robot Arm

3.1 Kinematic description of the robot arm

As shown in Figure 2 (Fig. 2), according to the Denavit-Hartenberg method, a mathematical model of a six-degree-of-freedom multi-joint robot is established to describe the relative positional relationship between industrial robot arms. As shown in Figure 2, according to the Denavit-Hartenberg method, a mathematical model of a six-degree-of-freedom multi-joint robot is established to describe the relative positional relationship between industrial robot arms. The coordinate information under the robot end coordinate system (7 system) is converted to the base coordinate system by Eq. (1):

$$\begin{align*}
T &= T(\theta_1)T(\theta_2)T(\theta_3)T(\theta_4)T(\theta_5)T(\theta_6)T(\theta_7)
\end{align*}$$

(1)

Where $T$ represents the rigid transformation matrix from the x coordinate system to the y coordinate system, and $\theta_1$ to $\theta_7$ represents the joint angles between the robot arms, which are the parameters of the transformation matrix between adjacent coordinate systems. If the conversion relationship between the robot end coordinate system and the elastic probe coordinate system is $T$, the data in the probe coordinate system can be unified into a base coordinate system by Eq. (2):

$$\begin{align*}
T &= T(\theta_1)T(\theta_2)
\end{align*}$$

(2)

It should be noted that, for the kinematics equations of the robot constructed by the simple D-H model, the measurement accuracy and repeatability level caused by the cumulative error of the kinematics structure are beyond the scope of this paper.

3.2 Elastic deformation model of elastic probe

The relative position information of the end point of the probe is obtained by analyzing the mapping relationship between the force and deformation of the elastic probe. Suppose the probe is a uniform beam with length $l$, density $\rho$, and cross-sectional area $A$. When the probe is under pressure equilibrium, only a space force vector wrench $W$ acts at the end, where $W = \begin{bmatrix} T & W \end{bmatrix}$ is an element of the
The components $\delta z(z)$, $f z$ and $\theta z(z)$ in the length direction along the Z axis are related by:

$$GJz \theta z(z) = zf z \tag{8}$$

$$EA \delta z(z) = zf z \tag{9}$$

Where, $E$ and $G$ are the elastic modulus and shear modulus of the probe material; $I_x$ and $I_y$ are the moment of inertia of the probe coordinate system $x$ and $y$ axis; $J_z$ is the moment of inertia of the cross section of the probe; $z$ represents Deformation at any point on the Z axis of the probe; $\tau_3$ and $f$ is an element of Lie algebra dual space.

Through formula (4) to formula (9), the relationship between the spatial deformation screws of the rod and the spatial force wrench $W$ can be established. When the tool coordinate system is established at the center of the end of the elastic probe, according to the kinematics theory, Eq. (10) and Eq. (11) are obtained.

$$s(l) = C_m W \tag{10}$$

$$C_m = \text{diag} \left( \frac{1}{EI_x}, \frac{l}{6I_y}, \frac{l^3}{12EI_y}, \frac{l^3}{12EI_x}, \frac{l}{EA} \right) \tag{11}$$

### 3.3 Force information collection and calculation processing

As shown in Figure 1, a six-dimensional wrist force sensor is fixed on the wrist of the robot, and an elastic probe is provided at the end of the six-dimensional wrist force sensor. By controlling the movement of the robot, the elastic probe is kept in proper contact with the surface of the object to be measured. At this time, in the sensor coordinate system, the relevant parameter information of the contact force between the probe and the measured object can be collected by the six-dimensional wrist force sensor:

$$F^{TR} = \left[ F_{ax} F_{ay} F_{az} M_{ax} M_{ay} M_{az} \right]^T \tag{12}$$
Where, $F_x$, $F_y$, $F_z$ is the three coordinate components of the force and $M_x$, $M_y$, $M_z$ represents the three coordinate components of torque when the probe is in good contact with the surface to be measured under the sensor coordinate system.

The parameter information of the force is transmitted to the computer by the data line, and the processing of the parameter information of the force is completed by the computer.

When the force (parameter matrix) in the sensor coordinate system is converted into that of the probe coordinate system (tool coordinate system), Eq. (13) can be obtained.

$$W = \frac{T R}{E} F^{TR}$$

Where, $\frac{T R}{E}$ is the posture of the sensor coordinate system under the tool coordinate system.

According to Eq. (10), the force at the contact point $P$ between the probe and the object under the tool coordinate system is transformed into the deformation under the coordinate system, and then equations Eq. (14) and Eq. (15) can be obtained.

$$S(l) = S_E - \Delta S = C_m W$$
$$S_E = \Delta S + (l) = \Delta S + C_m W$$

Where $\Delta S$ is the posture of the end point of the probe under the tool coordinate system before deformation and $S_E$ is the posture of the end point of the probe under the tool coordinate system after deformation.

Therefore, the coordinates of a point $P$ on the object in the tool coordinate system can be determined, and the coordinates in the tool coordinate system can be converted into the coordinates in the robot base coordinate system by employing Eq. (2). Then, Eq. (16) can be obtained.

$$S_0 = \frac{E}{R} S_E$$

4. Precision calibration based on visual measurement

The measurement object of the measurement system based on the robot arm is a large-scale complex curved surface part whose curvature is constantly changing. In order to effectively scan and calibrate the curved surface, the following constraints must be met when the visual photography system is working. $P_i$ and $N_i$ represent the $i$-th point calibrated on the surface and its unit normal vector respectively, and $B_i$ represents the bisector of the viewfinder boundary of the visual photography system. The calibration constraints of the visual photography calibration system include inclination, field of view (FOV), and depth of view (DOV) and so on.

4.1 Calibration of inclination of visual photography system:

The important assumption of visual guidance calibration is visual positioning, and the connection between the visual photography system and the measured point should be collinear with the normal vector of the measured point surface. However, in the actual measurement process, there is generally an angle $\theta$ between them (i.e., during the actual measurement, the visual camera system $L$ is connected to the measured point $P_i$, and the angle between it and the normal vector of the measured point, which is recorded as $\theta$). It should be noted that the included angle should be less than the constrained angle $\gamma$, which is set according to the requirements of specific parts.
As shown in Figure. 3(Fig. 3), the following relationship can be listed:

\[ d_i \cdot N_i \geq \cos(\gamma) \quad (17) \]

Where, \(-d_i\) is a unit vector,

\[ d_i = \frac{(L - P_i)}{|L - P_i|} \quad (18) \]

4.2 Field of view (FOV) calibration:
The scanning point should be within the length of the visual light corresponding to a certain visual system. The distance between the point on the measured surface and the laser head is different, and the effective fringe scanning length at different positions is constantly changing, so it is different from the ideal scanning situation. Assuming that the angle between \((-d)\) and \(B_i\) is \(\beta\), Eq. (19) can be obtained.

\[ (-d_i) \cdot B_i \geq \cos(\beta/2) \quad (19) \]

Where \(\beta\) is the wide angle of view.

4.3 Depth of field (DOF) calibration
The measured point must be within a specified range deviating from the visual system, and it should satisfy the Eq. (20)

\[ L_1 \leq |L - P_i| \leq L_2 \quad (20) \]

Where \(L_2 = L_1 + L_{DOF}\). \(L_{DOF}\) represents the depth of field value.

By the above three constraints, the appearance calibration of the special-shaped surface parts by the visual photography system can be realized.

5. Conclusion
Although the existing contact measurement technology has the disadvantages of slow measurement speed, easy to scratch the surface of the component, and a discontinuous measurement range, it is still a high-precision measurement method currently used in a large range. This paper realizes the automatic high-precision measurement technology of special-shaped parts based on the robot arm, which can be planned according to a certain path. In addition, by employing the principles of robot kinematics, the surface feature points of the measured object are measured in sequence, and the coordinates of each feature point in the robot's basic coordinate system are obtained. Finally, all data is automatically analyzed and processed by the computer, which can effectively improve the measurement efficiency. Meanwhile, precision calibration is performed through visual photogrammetry to ensure the validity of the measurement data.
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