Development of Orthros, an Evaluation System for Free Curved Plate Thickness with a Robot

-Selection of Representative Points for Appropriate Interpolation-

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Abstract:
This study deals with the development of an automatic system for measuring and evaluating the thickness of free curved plates, called Orthros. We proposed a method to generate a measuring path with high continuity of the measuring postures by using a quaternion to represent a change in posture with an interpolation algorithm, called squad. In this paper, a new method is proposed to determine the positions and postures of the representative points for interpolation that affect continuity of the measuring path. The validity of the proposed method was confirmed using evaluations of the continuity of a path according to changes in the joint angle of a robot.

Keywords: Industrial robot, Thickness measurement, Tool path, Path planning, Quaternion

1. Introduction
In general, thickness of sheet metal processed product with free curved surface is measured with point micrometer on the basis of the contact principle in the plastic processing field. However this measurement method is inappropriate to measure many points because it takes significant amount of time to measure[1] and it is difficult to measure the whole of workpiece with high density. Usually the several points that operator has determined are most often measured to evaluate the workpiece. Therefore, we proposed an automatic system for measuring and evaluating the thickness of free curved plates using laser displacement gauges and an industrial robot, called Orthros[2]. Although this system has been capable of measuring a workpiece with a relatively simple shape, it had collisions between the laser path and a workpiece with complicated shape, as a result of the geometrical limit for the measuring postures of the gauges. Then, it is necessary for the system to detect collisions and avoid these by changing the measuring posture through the use of CAD data. However, the laser displacement gauges used in the system have measurement error characteristics that depend on the measuring posture. The system generates a measuring path considering the continuity of the measuring postures to speed up the measurement in addition to the above problems. We proposed a method to generate a measuring path with high continuity of the measuring postures by using a quaternion to represent a change in posture with an interpolation algorithm presented by Shoemake, called squad (spherical and quadrangle)[3]. In this paper, a new method is proposed to determine the positions and postures of the representative points for appropriate interpolation. In addition, the validity of the proposed method was confirmed through evaluations of the continuity of a path depending on changes in the joint angle of a robot.

2. Outline of Orthros

2.1 Configuration of the system
Figure 1 shows the configuration of the system. A dual-head thickness measuring unit composed of two laser displacement gauges, which are placed to share the same optical axes, measures the thickness of a workpiece. The system uses two LK-G150 gauges (Keyence Co., reference distance of 150 mm, spot diameter of $\phi 120 \mu m$, and positioning accuracy of $\pm 0.04 \text{ mm}$) as laser displacement gauges. The system uses a vertical articulated industrial robot, HP-6 (Yasukawa Electric Co., payload of 6kg and positioning accuracy of $\pm 0.08 \text{ mm}$), as a workpiece positioning device.

2.2 Principle of the measurement procedure
The basic measurement procedure is as follows[2].
1) Measure shape of workpiece with a laser displacement gauge.
2) Generate normal vector at each measuring point according to the workpiece shape.

Figure 1: Configuration of the system.
3) Generate a series of postures for the robot to match the normal vector and the optical axis of the laser as a measuring path. A posture when the laser is vertically incident on the measuring surface is defined as a basic posture. A triangular area surrounded by the laser irradiation light, reflected light, and gauge is defined as the laser-path area.

4) Measure the workpiece thickness according to the measuring path.

3. Evaluation of posture using C-Space

In the case of a workpiece with a complicated shape, it is possible to have collisions between the laser-path area and the workpiece because of the geometrical limit for the measuring postures of the gauges, as shown in figure 2. The system avoids collisions by changing the posture from the basic posture. Because we define a coordinate system \( \{B_i\} \) (i-th measuring point) where the \( x \)-axis represents the normal direction of each measuring point and the \( z \)-axis represents the measuring process direction, as shown in figure 3, the measuring posture is represented by rotational angles \( \gamma_{Bi}, \beta_{Bi}, \) and \( \alpha_{Bi} \) (roll, pitch, and yaw) around the \( x_{Bi}, y_{Bi}, \) and \( z_{Bi} \) axes, respectively. The posture having \( \gamma_{Bi}=\beta_{Bi}=\alpha_{Bi}=0^\circ \) represents basic posture. According to the previous research[4], in pitch, the measurement errors increase enormously in case of \( \beta_{Bi} \) is in the range of -11° to -6° as shown in figure 4 because of the increase in the regular-reflection component from the measuring surface. The postures in this range are defined as regular-reflection postures, and the system has no ability to measure where the posture has a pitch value in the regular-reflection postures. The accuracy in other areas of the above pitch, roll, and yaw angle range is not lower than almost ±0.04 mm in the range of -40° to 40°.

We apply a 3D configuration space (C-Space)[5] to deal with the geometric collisions and measurement error characteristics in the same manner. The system uses a C-Space defined by rotational angles \( \gamma_A, \beta_A, \) and \( \alpha_A \) around the \( x_A, \) \( y_A, \) and \( z_A \) axes of coordinate system \( \{A\} \), where the \( x \)-axis represents the laser irradiation direction, and the \( z \)-axis represents the vertical direction defined as shown in figure 2, for each measuring point, to consider the continuity of the measuring postures. The postures that are collision free, regular-reflection free, and within the range of ±40° to the basic posture in the coordinate system \( \{Bi\} \) are mapped in the C-Space. The postures mapped in the C-Space and

![Figure 2: Collision between laser and workpiece.](image)

![Figure 3: Definition of coordinate system \( \{Bi\} \).](image)

![Figure 4: Relationship between angle and error (pitch).](image)

![Figure 5: C-Space mapped measurable postures.](image)

![Figure 6: Interpolation of rotation with slerp.](image)
which are measured without collision with the nominal specification accuracy are called measurable postures. Figure 5 shows these measurable postures in the C-Space.

4. Smooth interpolation of measuring postures by use of squad

The system determines the measuring posture by selecting an arbitrary posture from the measurable postures mapped in the C-Space on each measuring point. Although the representation of a posture by the use of the C-Space is appropriate for representing a static condition, it is difficult to select the most continuous set of postures in multiple C-Spaces. In this study, to generate a measuring path with a high continuity of measuring postures, we apply the quaternion used in 3D computer animations\[6-9\] and the posture calculation for a flying object\[10,11\] to represent a change in posture, by using the popular interpolation algorithm called squad\[3,12\]. Squad is the only algorithm that interpolates serial postures of more than three points to define a path continuously. Quaternion $q$ has four elements, a set of a scalar element and a 3D vector element.

$$ q = [w, x, y, z] = [w, \mathbf{v}] $$

(1)

Given the quaternion as a 4D vector, a formula for squad from $q_n$ to $q_{n+1}$, with parameter $t$ moving from 0 to 1, can be obtained as

$$ \text{squad}(t; q_n, q_{n+1}, a_n, a_{n+1}) = \text{slerp}(2t(1-t); \text{slerp}(t; q_n, q_{n+1}), \text{slerp}(t; a_n, a_{n+1})) $$

(2)

Slerp (spherical liner interpolation) is an algorithm that interpolates between the continuities of two postures. $\text{slerp}(t; q, q_{n+1})$ is defined as

$$ \text{slerp}(t; q, q_{n+1}) = \frac{q_n \sin(\theta(1-t)) + q_{n+1} \sin(t\theta)}{\sin\theta} $$

(3)

Here, $\theta$ is the angle between $q_n$ and $q_{n+1}$, as shown in figure 6 and defined as

$$ \theta = \cos^{-1}(q_n \cdot q_{n+1}) $$

(4)

Scalar product of quaternion $q_n$ and $q_{n+1}$ is calculated as

$$ q_n \cdot q_{n+1} = w_n w_{n+1} + x_n x_{n+1} + y_n y_{n+1} + z_n z_{n+1} $$

(5)

In addition, $a_n$ is defined as follows:

$$ a_n = q_n \exp(-\log(q_{n-1}^{-1} \cdot q_n) + \log(q_n^{-1} \cdot q_{n+1})) $$

(6)

$a_n$ is the quaternion sequence that the derivative of squad is continuous on control point, with parameter $t=0$ and 1. In other words, if $S_n' (t) = \text{squad}(t, q_n, q_{n+1}, a_n, a_{n+1})$, $a_n$ is the quaternion sequence that $S_n' (0) = S_n' (1)$ in all $n$. For calculation $a_n$, some operations of the quaternion are required. The reciprocal of $q$ is defined as

$$ q^{-1} = \left[ w - \mathbf{v} \right] $$

(7)

Multiplication of quaternion $q_n$ and $q_{n+1}$ is defined as

$$ q_n q_{n+1} = \left[ w_n w_{n+1} - \mathbf{v}_n \cdot \mathbf{v}_{n+1}, w_n \mathbf{v}_n + w_{n+1} \mathbf{v}_{n+1} + \mathbf{v}_n \times \mathbf{v}_{n+1} \right] $$

(8)

For calculation of logarithm, variables $\sigma$ which is equal to half of the rotational angle $\theta/2$ is defined and the quaternion $p$ is reformulated as follows:

$$ \sigma = \theta / 2 $$

(9)

$$ |\mathbf{n}| = 1 $$

(10)

$$ p = [\cos \sigma, \mathbf{n} \sin \sigma] $$

(11)

$$ p = [\cos \sigma, x \sin \sigma, y \sin \sigma, z \sin \sigma] $$

Here, the logarithm of $p$ is defined as follows:

$$ \log p = \log(\cos \sigma, \mathbf{n} \sin \sigma) $$

(12)

$$ \log p = [0, \sigma \mathbf{n}] $$

(13)

$$ |\mathbf{n}| = 1 $$

(14)

$$ \exp r = \exp(\mathbf{0} \cdot \mathbf{n}) $$

(15)

$\exp r$ is the quaternion of unit length. From the above, squad needs $q_{n+1}$, $q_n$ and $q_{n+1}$, $q_{n+2}$ for the interpolation between $q_n$ and $q_{n+1}$. If the required quaternions for squad include that of the end point of the path, copied quaternions are given. We assign 0 to $w$ and a 3D vector of unit length representing the measuring posture to $\mathbf{v}$ in the quaternion. Figure 7 shows an example of the 3D vector interpola-
tion, with arrow vectors showing representative directions. Because the measuring direction of the system is unidirectional, as shown in figure 8, a set of measuring points in a column is defined as a measuring-path element. In this paper, the system considers the continuity in a measuring-path element.

5. Determination of representative points and initial postures

The system defines the representative points from the start point and end point of a measuring-path element. It calculates the centroid coordinate of measurable postures mapped in the C-Space on each point in a measuring-path element, and local maximum value of the distance between centroid coordinate of adjacent points. Then it compares the measurable postures mapped in the C-Space of the points around the points having the local maximum value, and determines the other representative points in the following two methods:

1) The point having the local maximum value is defined as representative point when the three measurable postures have the common postures.
2) The points around the points having the local maximum value are defined as representative points when the three measurable postures don’t have the common postures.

The measuring posture on the representative point is defined as the initial posture. It is defined as the initial posture that the posture with the centroid of the common postures in 1), the posture with the minimum distance from the origin of the C-Space in 2), respectively.

6. Generation of measuring path

The procedure to generate a measuring path using squad is as follows:

1) The system detects collisions at the basic posture on each measuring point.
2) It maps measurable postures in the C-Space on each measuring point in the measuring-path element, including the points where collisions have been detected in 1), as shown in figure 5.
3) It determines the representative points and the initial postures.
4) It interpolates between the measuring postures of the representative points determined in 3) by using squad. It verifies whether the interpolated postures are measurable postures. If there are unmeasurable postures, it defines the points as new representative points and interpolates again. It repeats this process until all the postures fit into the measurable postures. It generates the measuring path in the basic postures if there are no collisions in a measuring-path element.

7. Experiment

A measuring experiment was carried out to verify the validity of the generated measuring path. Figure 9 shows the workpiece and measured area, and table 1 lists the experimental conditions. The C-Space was generated within a range of ±20° at intervals of 5°, considering the calculation cost to detect collisions. Figure 10 shows the thickness distribution map, and figure 11 shows one column of the generated measuring path. It shows that the system could measure the thickness of the workpiece at all the measuring points. The thickness of the machined part is expected to have been small, and the thickness measurement by the system reflects this tendency. Figure 12 shows the measurement errors of the system in reference to measurements.
with a point micrometer in a measuring-path element. All the errors were within the range of the designed accuracy of the system.

In this paper, we evaluate the continuity of the measuring path from change in the joint angle of the robot. To stabilize the high-speed robot motion, it is necessary to make angular acceleration of the joint angle smaller without sudden change in posture. Figure 13 shows the changes in the angular displacement, angular velocity, and angular acceleration of a six-axis robot in a measuring-path element of the two paths to compare the continuities. Path1 shows the generated path by the proposed method, and path2 shows the interpolated path from the same representative points as path1 but with the different initial posture taken the minimum distance from the origin of C-Space. Figure 13(a) shows that although the variation range of path2 is smaller, path2 is discontinuous in the middle, and figure 13(c) shows that the maximum value of path1 is lower. These data led us to the conclusion that the system could measure the thickness of the workpiece with complicated shape, and the generated path had high continuity for the measuring postures.

8. Conclusion
This study proposed a method for determining the representative points and the initial postures to generate a thickness measuring path with high continuity of the measuring postures using squad interpolation algorithm. From the experimental results, this paper can be summarized as follows:
1) From the distance between the centroid coordinate of measurable postures mapped in the C-Space of adjacent points and common postures of them, the system could determine the positions and postures of the representative points for appropriate interpolation using squad.
2) In the experiment to measure the thickness of a workpiece with a complicated shape using the generated measuring path, the system could measure the thickness within designed accuracy range.
3) The evaluation results with changes in the joint angle of a robot showed that the generated path had high continuity.

References


