Articulated Robot Application in End Milling of Sculptured Surface*

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End milling of a sculptured surface is attempted employing an articulated robot with six degrees of freedom. In this application, the machining error due to the positioning accuracy and elastic deformation of robots should be considered. In order to improve positioning accuracy, a new robot calibration method has been developed and applied. After the calibration, the robot is operated by off-line teaching programs effectively, and experimental end milling is finished with improved machining accuracy. Furthermore, a postprocess error compensation has been realized to minimize the machining error caused by all of factors such as the positioning error, elastic deformation and joint backlash of the robot. Experimental end milling shows that the machining accuracy is improved to near the positioning repeatability of the robot after repeating compensation twice. Additionally, a sensor feedback teaching method which is another way to achieve end milling of a sculptured surface has been developed.

Key Words: Robot, Milling, Machining Accuracy, Robot Calibration, Postprocess Error Compensation, Sensor Feedback Teaching

1. Introduction

In recent years, studies on the robot utilization in the machining field have been actively under way, and its application to auxiliary tasks such as deburring, polishing, and grinding is being attempted\(^{(1)}\) \(^{(4)}\). However, robots are rarely employed in the field of cutting\(^{(5)}\), because such realization requires the solution of problems, including (1) low rigidity of robots themselves, (2) low positioning accuracy of them, and (3) insufficient teaching method by teaching playback method in which teaching operation of milling is incredibly difficult. Meanwhile, vertical type articulated robots commonly adopted for welding have wide operation regions along with high degrees of freedom, and the authors target positive utilization of these advantages in milling. In particular, our research is under way to solve the above problems for the trial machining of parts designed by CAD.

In order to improve positioning accuracy of the robot employed and perform off line programming function, a new robot calibration method has been developed and applied. Good performance of the calibration method proposed is confirmed by experimental end milling\(^{(6)}\). Furthermore, a postprocess error compensation has been realized to minimize the machining error caused by all of factors, such as the positioning accuracy, elastic deformation and joint backlash of the robot. Experimental end milling shows that the machining accuracy is improved to near the positioning repeatability of the robot after repeating compensation twice\(^{(7)}\). Additionally, a sensor feedback teaching system which is another way to achieve end milling of a sculptured surface has been developed\(^{(8)}\).

2. Robot Calibration

Off line teaching of a robot is the most important function to perform many kinds of tasks with higher accuracy. In this function, the nominal geometry of a computer model representing the robot controlled have to agree with the actual geometry of this robot. The biggest problem is that the manufacturing tolerances, assembling errors, setting errors etc. are involved in the actual geometry of the robot. And the
discrepancy between the nominal geometry and the actual one generates the positioning error of the robot.

Robot calibration involves the identification of a more accurate relationship between the nominal geometry and the actual one, because the positioning accuracy of robot can be improved when the nominal geometry of a computer model is corrected according to this identified relationship. Many kinds of measurements are performed by several researchers for their robot calibrations. Whitney et al. [9] and Judd et al. [10] used a theodolite known as a surveyor's telescope for their measurement. The theodolite measurement is difficult for an inexperienced operator. Also, it needs a length standard to determine the lengths from measuring angles. Veitschegger et al. [11] used an external fixture. Measurement accuracy is affected by locating the fixture in the robot working space. Vira et al. [12], Mooring et al. [13] and Heeren et al. [14] used a ball bar, a 3D coordinate measuring machine and a laser tracking system, respectively. All of this equipment has enough accuracy, but their measuring space is limited. An ultra sonic sensor [15] and a stereo vision system [16] are used for measurement. But measuring data from this equipment lacks resolution. Moreover, these calibration methods need 3D (or 2 D) position data on specified points of a robot at several configurations, and it is important to know the location of the measuring equipment. We think that the difficulty of 3D position measurements disturbs the effective calibration of an articulated robot especially one which has a wide working space.

In this study, we introduce a new calibration method which needs only the moving distance errors of an end effector of a robot. The moving distance between the initial position of the end effector and any later position can be measured exactly and easily by a laser interferometer. A laser interferometer detects motion with better accuracy and higher resolution. But it can be used only for linear motion. We therefore adopt a new procedure in which accurate geometric parameters of a robot are identified from moving distance errors in measuring direction.

3. Mathematical Model for Robot Calibration

Denavit and Hartenberg established the most popular modeling method of a robot [17], but it is well known that a problem arises when two successive rotational joints are parallel. In this study, a general coordinate system with 6 degrees of freedom was adopted for each joint. Figure 1 illustrates the relation between the coordinate systems of the \(i\) th and \((i+1)\) th joints of a robot. The translation between the origin of the \(i\) th joint \(P_i\) and that of the \((i+1)\) th joint \(P_{i+1}\) is represented by \(l_i\), \(m_i\), and \(n_i\) in the directions from the origin \(P_i\) to the \(X_i\), \(Y_i\), and \(Z_i\) axes, respectively. Furthermore, the \(Z_i\) axis of the coordinate system is determined to agree with the direction of the joint rotational axis, and the \(P_{i+1}\) coordinate system is prepared by rotating the \(P_i\) coordinate system around the \(Z_i\) axis by \(\theta_i\) (joint rotational angle), and then around the \(X_i\) axis by \(\alpha_i\) as well as around the \(Y_i\) axis by \(\beta_i\). The transformation matrix between two successive joints \(P_i\) and \(P_{i+1}\) is represented by the following form:

\[
A_i = \begin{bmatrix}
    C\theta_i & -S\theta_i & 0 & l_i \\
    S\theta_i & C\theta_i & 0 & m_i \\
    0 & 0 & 1 & n_i \\
\end{bmatrix}
\]

where \(C\) stands for cos, and \(S\) for sin.

When the coordinate system shown in Fig. 1 is defined for each joint of the 6 axis vertical type articulated robot (Maximum loading weight: 60 kg; Pana Robo AW 8060 ; Matsumoto Industrial Equipment Co., Ltd.) employed in this study, parameters between coordinate systems are obtained as in Fig. 2. Among them, \(l_i \sim l_{i+1}\), \(m_i \sim m_{i+1}\), \(n_i \sim n_{i+1}\), \(\alpha_i \sim \alpha_{i+1}\), and \(\beta_i \sim \beta_{i+1}\) are determined from the structures and dimensions of the robot; and \(l_0\), \(m_0\), \(n_0\), \(\alpha_0\), and \(\beta_0\) are determined from those of an end effector installed on the robot. The transformation matrix \(T_i\) to express the position and orientation of the end effector shown in the reference coordinate system of the robot is as follows:

\[
T_i = \begin{bmatrix}
    a_x & a_y & a_z & p_x \\
    b_x & b_y & b_z & p_y \\
    c_x & c_y & c_z & p_z \\
    0 & 0 & 0 & 1 \\
\end{bmatrix}
\]
where $n=(n_x, n_y, n_z)^T$, $a=(a_x, a_y, a_z)^T$ and $a=(a_x, a_y, a_z)^T$ are unit vectors to represent the orientation of the end effector, and $p=(p_x, p_y, p_z)^T$ is a vector to represent the position of the end effector tip. Applying the relations Eqs. (1) and (2), the position of the end effector tip can be obtained as a function of the parameters which show the structures, dimensions and joint angles of the robot.

$$p = F(Q)$$  \hspace{1cm} (3)

where $Q$ is the robot parameters vector organized by $h_i, l_i, m_i, n_i, a_i$ and $\theta_i$. The position error vector $\Delta p$ can be expressed as the following form,

$$\Delta p = (\partial p / \partial Q) \Delta Q$$  \hspace{1cm} (4)

where $\Delta Q$ corresponds to the error vector which is identified by the robot calibration. The moving distance error $\varepsilon$ can be derived from the position error vectors $\Delta p_0$ and $\Delta p_0$ corresponding to before and after linear motion of the end effector, respectively.

$$\varepsilon = |\Delta p_0 - \Delta p_0| = (\partial p / \partial Q) (\partial p / \partial Q) \Delta Q$$  \hspace{1cm} (5)

4. Identification of Accurate Robot Geometry

Generally, the joint encoder offsets $\Delta \theta_i$ contributes substantially to the positioning error against $\Delta a_i$ and $\Delta \beta_i$. So we assumed that $\Delta a_i = \Delta \beta_i = 0$ for all $i$ th joints in order to simplify the identification. Equation (5) can be rewritten as follows,

$$\varepsilon = (\partial p / \partial Q) (\partial p / \partial Q) \Delta Q$$

$$= \sum_i [(\partial p / \partial \theta_i) - (\partial p / \partial \theta_i)] \Delta \theta_i$$

$$+ \sum_i [(\partial p / \partial l_i) - (\partial p / \partial l_i)] \Delta l_i$$

$$+ \sum_i [(\partial p / \partial m_i) - (\partial p / \partial m_i)] \Delta m_i$$

$$+ \sum_i [(\partial p / \partial n_i) - (\partial p / \partial n_i)] \Delta n_i$$

$$= \sum_i \theta_i \Delta \theta_i + \sum_i L_i \Delta l_i + \sum_i M_i \Delta m_i + \sum_i N_i \Delta n_i$$  \hspace{1cm} (6)

Accurate robot geometry can be identified by solving simultaneous equations composed by Eq. (6), but it was found that some of the parameters $\Delta \theta_i, \Delta l_i, \Delta m_i, \Delta n_i$ were not independent by comparison of $\theta_i, L_i, M_i$ and $N_i$. For example, Fig. 3 shows that the positioning error at the robot end effector tip can be represented by only two parameters among $\Delta l_i, \Delta m_i$ and $\Delta n_i$. In this case, $\Delta l_i, \Delta m_i$ and $\Delta n_i$ are not independent, so $\Delta l_i$ and $\Delta m_i$ can be identified when it is assumed $\Delta l_i = 0$. It means that the actual value of $\Delta l_i$ is included implicitly in $\Delta m_i$ and $\Delta n_i$. (Although the identified values of $\Delta l_i$ and $\Delta n_i$ will change according to the value of $\Delta \theta_i$, but the positioning error of the robot end effector tip is represented by the same values. In strict, the orientation of the robot end effector will change according to the difference values of $\Delta l_i, \Delta m_i$ and $\Delta n_i$, but the change of the orientation is negligible small.) Same situation happens at several combinations of the parameters such as $(\Delta m_i, \Delta n_i, \Delta l_i)$, $(\Delta l_i, \Delta m_i)$, $(\Delta m_i, \Delta l_i)$, $(\Delta n_i, \Delta l_i)$ and $(\Delta l_i, \Delta m_i, \Delta n_i)$.
Moreover, $\Delta \theta_6$ and $\Delta n_6$ were not identified because they have the same effect as some position and orientation errors of the robot base coordinate system with respect to the world coordinate system. But, they do not have any effect against the dimensional error of machining parts. This problem arises against the advantage that it does not need to know the location of measuring equipment.

Finally, 15 parameters were identified explicitly and 7 parameters implicitly. In order to identify these parameters, 273 moving distance errors were obtained from the machining space in front of the robot. A moving distance error was defined as the difference between a nominal moving distance and an actual one. Actual moving distances were detected using a laser interferometer measuring equipment (Measuring resolution: 2.49 nm (nano-meter) for linear motion; AXIOM 2/20; ZYGO Co., Ltd.) at 91 measuring points on 13 measuring lines along $X$, $Y$, and $Z$ axes shown in Fig. 4. Every measuring line was 600 mm, and measuring points were fixed at every 100 mm step movement on each measuring line. Actual moving distances were measured in both the positive and the negative direction of each measuring line to diminish the effect of joint backlash. Simultaneous equations were solved using a generalized inverse matrix (the Moore-Penrose inverse matrix)\(^{40}\) to avoid the singular problem in parameter estimation. Finally, the geometric errors given in Table 1 were identified by this robot calibration.

### 5. Results of Robot Calibration and Experimental End Milling

In order to evaluate the performance of this calibration method, moving distances were measured at 105 measuring points on 15 measuring lines along $X$, $Y$, and $Z$-axes. Moving distance errors obtained from these results are shown in Fig. 5. The results of before and after the calibration are represented by marks without and with shading, respectively. Moving distance errors reduce fairly well after the calibration in every measuring lines. Especially, the last two graphs (IV and V) in Fig. 5 indicate good performance of this calibration method. Because

\[\text{Table 1 Results of robot calibration proposed}\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal values</th>
<th>Identified geometric errors</th>
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</thead>
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<tr>
<td>$\theta_1$</td>
<td>$\theta_1$</td>
<td>0 (can not be identified)</td>
</tr>
<tr>
<td>$l_1$</td>
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</tr>
<tr>
<td>$m_1$</td>
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<td>3.326</td>
</tr>
<tr>
<td>$n_1$</td>
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<td>0 (can not be identified)</td>
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<tr>
<td>$\theta_2$</td>
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</tr>
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<td>$l_2$</td>
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<tr>
<td>$m_2$</td>
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<td>2.591</td>
</tr>
<tr>
<td>$n_2$</td>
<td>0</td>
<td>0 (included in $\Delta n_2$)</td>
</tr>
<tr>
<td>$\theta_3$</td>
<td>$\theta_3$</td>
<td>0.000421</td>
</tr>
<tr>
<td>$l_3$</td>
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<td>$m_3$</td>
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<td>$\theta_4$</td>
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</tr>
<tr>
<td>$\theta_6$</td>
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</tr>
<tr>
<td>$n_6$</td>
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<td>0 (included in $\Delta n_6$)</td>
</tr>
</tbody>
</table>

Length in millimeters, angle in radians

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moving distance errors of these two measuring lines reduce as well in spite of the fact that they did not participate in the identification of geometric errors of the robot. The root mean squared (RMS) value of the moving distance errors per 100 mm step movement decreases from 567 μm to 107 μm. The value of 107 μm is less than the 200 μm positioning repeatability of the robot employed, and moving distance errors for 600 mm travel do not exceed 300 μm.

Experimental end milling was conducted to compare the machining accuracy between before and after the robot calibration. Two fluted ball nose HSS 10 mm diameter end mill was employed as a cutting tool, and industrial plastic (Trade name: Juracon) as a work to be machined. Target shape for experimental end milling is shown in Fig. 6. The position and orientation of the tool were operated as shown in Fig. 6, the tool inclines from the initial orientation and moves straight (1~3), moves along an arc keeping the tool axis normal to the arc (3~7), moves straight and raises up to the initial orientation (7~9). Off line teaching programs of the robot which correspond to before and after the robot calibration were prepared in a personal computer to realize the position and orientation of the end mill mentioned above.

Figure 7 shows the machining accuracy obtaining before and after the robot calibration. The machining accuracy was detected by 3D coordinate measuring machine (GS 600 C, Tokyo Seimitsu Co., Ltd.). In these results, elastic deformation, joint backlash of
the robot were included besides positioning error. The first graph represents that the tool tip swings along X-axis according to the feed motion along Y-axis. Especially before the robot calibration, the maximum swing is approximately 6 mm and extremely large. After the robot calibration, the maximum swing is approximately 1.5 mm and still large. In this case, the root mean squared (RMS) value of the machining accuracy decreases from 3036 μm to 1261 μm.

The last two graphs in Fig. 7 represent the machining accuracy in YZ plane which show the difference between the target shape and the machining shape. Before the robot calibration, the discrepancy of the circularity is recognized. After the calibration, it was improved but 1.5 mm difference of height between two base lines which were machined straight. In this case, the root mean squared (RMS) value of the machining accuracy decreases from 1559 μm to 1192 μm.

After the robot calibration the machining accuracy became better than that before the calibration, but it has still problems. Especially, the positioning error might become large owing to changing of the tool orientation. The reason why is supposed that elastic deformation of the robot caused by gravity is not taken into account in the robot calibration although it is affected by the tool orientation or the robot configuration. Additional research should concentrate on the more effective robot calibration to improve the positioning accuracy in any robot configuration.

At last, an example of milling by an articulated robot is shown in Fig. 8. It is a relief modeling of the "Kotoji" stone lantern in Kenroku Garden, Kanazawa. Two fluted ball nose HSS 6 mm diameter end mill was employed as a cutting tool, and industrial plastic (Trade name: Juracon) as a work to be machined. The performance of milling by an articulated robot with high degrees of freedom was confirmed by this experimental end milling.

6. Postprocess Error Compensation to Improve Machining Accuracy

Postprocess error compensation is another method to improve the machining accuracy. The machining accuracy is improved by correcting robot movement through feedback of the machining error. In this method, all of factors to lower machining accuracy, such as the positioning error of robots, elastic deformation, and joint backlash are compensated. In order to correct the robot movement, the relation between the correction amount of joint angles to determine the robot configuration and the machining error must be clarified. Minute changes in the position and orientation of the tool tip when joint angles are minutely changed are expressed using following matrix consisting of minute translational and rotational vector elements.

\[
\begin{align*}
[\text{i}^*d_x] & = \begin{bmatrix}
[\text{i}^*d_{dx} ] \\
[\text{i}^*d_{dy} ] \\
[\text{i}^*d_{dz} ]
\end{bmatrix} + \begin{bmatrix}
[\text{i}^*d_{dx} ] \\
[\text{i}^*d_{dy} ] \\
[\text{i}^*d_{dz} ]
\end{bmatrix} \frac{\text{d} \theta}{\text{d} \phi} \\
[\text{i}^*\delta_x] & = \begin{bmatrix}
[\text{i}^*\delta_{dx} ] \\
[\text{i}^*\delta_{dy} ] \\
[\text{i}^*\delta_{dz} ]
\end{bmatrix} + \begin{bmatrix}
[\text{i}^*\delta_{dx} ] \\
[\text{i}^*\delta_{dy} ] \\
[\text{i}^*\delta_{dz} ]
\end{bmatrix} \frac{\text{d} \phi}{\text{d} \theta} \\
\end{align*}
\]

(7)

This matrix is known as Jacobian Matrix, and its derivation process is described in details in the Ref. (18). The robot movement is corrected by updating the joint angle information in the teaching program, and the minute correction amount of each joint
angle is obtained by solving Eq. (7) based on the machining error.

Figure 9 shows an example of machined shape before error compensation. Two fluted ball nose HSS 6 mm diameter end mill was employed as a cutting tool, and industrial plastic (Trade name: Juracon) as a work to be machined. Enhanced machining error is illustrated schematically in Fig. 9. The machined peak shapes are deviated to the left or right side depending on the tool feed direction which is along Y axis and different row by row.

The machined shape of the second row among the seven tool paths, which is compared before and after postprocess error compensation, is shown in Fig. 10. In this figure, the designed shape to be machined is represented by solid lines, and machined shapes before and after compensation with broken lines and dotted lines, respectively. Figure 10 reveals that the machining error was reduced successfully by postprocess error compensation.

Figure 11 summarizes the relation between compensation iteration and machining accuracy. The machining accuracy was expressed with the sum of squares of error from designed shape at each measuring points of 3 rows in the positive feed directions (3rd, 5th and 7th rows) and 3 rows in the negative feed directions (2nd, 4th and 6th rows) so that a difference in tool feed directions could be compared. In this case, the measuring points correspond to lattice points indicating the machined surface in Fig. 9, and count to 121 points for each row. It is found that a difference in machining accuracy caused by a different tool feed directions before compensation almost disappeared after compensation. Furthermore, it is revealed that when postprocess error compensation is repeated twice the machining accuracy is improved to the near the limit. The root mean squared (RMS) value of the machining accuracy having been approximately 100 μm before compensation was found to be approximately 40 μm after repeating compensation twice. This value is almost equal to the positioning repeatability of the robot employed, and is the limit of machining accuracy using an articulated robot.

7. Copy Milling Based on Sensor Feedback Teaching

In sensor feedback teaching, the position and orientation of robot hand tip are calculated with a computer based on robot joint angles. Furthermore, the position and orientation of robot hand tip are
controlled in order to maintain the distance from the robot hand tip to the model with shape to be machined. Consequently, if a model with shape to be machined can be prepared, a robot teaching program for end milling will be coded accurately and automatically. In addition, this teaching method is also applicable to teaching for welding, deburring, and grinding.

In order to control the robot movement, the minute correction amount of each joint angle must be calculated from minute translational and rotational vector elements corresponding to the correction of robot configuration. Actually, the minute displacement to the target robot configuration was calculated to maintain the distance from the robot hand tip to the model with shape to be machined, and then the robot configuration was controlled on the basis of the minute correction of each joint angle obtained by solving Eq. (7).

Figure 12 represents the accuracy of the teaching program coded by the sensor feedback teaching method. In this case, the teaching program was coded by tracing a model with curved surface along Y axis at 201 teaching points with 1 mm interval. Although numerical convergence error was set to 0.2 mm when the teaching program was coded, the teaching error exceeded this value at some teaching points, resulting in approximately 0.5 mm at a maximum. The teaching error becomes large at the parts of large gradients of model. It is supposed that the used laser displacement sensor does not detect accurate distance at the parts with larger gradients because it detects displacement on the basis of the reflection angle of laser light. In another case, when the teaching program was coded by tracing a flat model, the teaching error is smaller than this case.

Experimental copy milling was performed to confirm the effectiveness of sensor feedback teaching method. The mask of Mickey Mouse was adopted as a model, and a teaching program was coded which had approximately 12,000 teaching points consisting of lattice points at intervals of 2 mm in the XY plane. The mask is provided with white painting to allow sufficient reflection of laser light, and sensor feedback teaching is performed as shown in Fig. 13. Although the convergence time was longer at parts with great gradients on the model surfaces where measurement with the displacement sensor was inaccurate, the teaching program was coded spending about 35 hours for all teaching (about 10 seconds per single teaching point). With respect to the problem of teaching time, the teaching time will become 100 times shorter if it is possible to control the robot directly, because now it is controlled through a teaching box for a teaching playback operation. Accomplished relief by the experimental copy milling is shown in Fig. 14. Two fluted ball nose HSS 6 mm diameter end mill was employed as a cutting tool, and machinable wax as a work to be machined. As mentioned above, the sensor feedback teaching method had some problems with teaching accuracy and teaching time, but still realization of copy milling confirmed its effectiveness.

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Fig. 13 Experimental teaching by sensor feedback method
Fig. 14 Accomplished relief by experimental copy milling
8. Conclusions

End milling of a sculptured surface was attempted employing an articulated robot with six degrees of freedom. In this application, the machining error due to the positioning accuracy and elastic deformation of the robot should be considered. The following conclusions were obtained through several experimental end milling.

(1) In order to improve the positioning accuracy, a new robot calibration method has been developed and applied. After the calibration, the robot is operated by off-line teaching programs effectively, and the experimental end milling is finished with improved machining accuracy.

(2) The postprocess error compensation has been realized by correcting the robot teaching program to minimize the machining error. The machining accuracy is improved to near the positioning repeatability of the robot after repeating compensation twice.

(3) The sensor feedback teaching method has been developed in which a robot is controlled in order to trace a model to be machined for automatic coding of the teaching program. This teaching method is also applicable to teaching for welding, deburring, and grinding.

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