OPTIMIZATION OF WORKPIECE PLACEMENT IN SEALING OPERATION USING INDUSTRIAL ROBOT CONSIDERING MANIPULABILITY

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ABSTRACT

Off-line teaching systems are becoming the mainstream method of making a robot program, as opposed to a teaching playback method that requires the technical skill of a worker. The off-line teaching system enables to make the robot program on a computer and allows the simulation of robot motion by checking the program. However, to make an optimal program with consideration to the prevention of sudden change in the robot’s motion, singularity should be avoided and workpiece placement should be optimized. In particular, to determine the workpiece placement, the operator must perform many trial and error operations.

In this paper, we propose an optimization method for workpiece placement during a sealing operation by using an industrial robot. This method is based on manipulability, which is a measure of the robot’s manipulating ability. We confirmed the effectiveness of the proposed method by applying it to an actual sealing process.

INTRODUCTION

At a manufacturing production site, vertical articulated industrial robots are widely used to automate various operations, owing to their high versatility and operability. Typical examples of this application include the assembly, welding, painting, sealing, and handling of material.

To operate an industrial robot, it is necessary to create a robot program that consists of end effector position/posture or joint angle sets. Typically, the operator makes the robot program by using the teaching playback method, which requires various operations through a special control device called the teaching pendant. Although the operator can make the robot program intuitively by using an actual robot, the teaching operation is time consuming. Moreover, the production cost may increase substantially because the production line must be stopped during the teaching operation.

In recent years, an off-line teaching method, which can make a robot program by operating the robot in a virtual space, has been developed and is becoming a mainstream method of robot program creation. By using this method, the time for stopping the production line and the labor entailed in the operation of an actual robot may be reduced.

Moreover, to conduct an optimal operation, the operator must determine the workpiece placement in order for the robot to perform the task safely, which requires many trial and error operations. Thus, some studies have proposed to optimize the robot program [1-3] and automate actual operations such as the polishing process [4-6]. However, it has been difficult to use these methods in practice.

In this paper, we propose a method based on manipulability, which is a measure of the robot’s manipulating ability [7], with the objective of optimizing the workpiece placement. Moreover, we have confirmed the effectiveness of the proposed method by applying it to an actual sealing process.

RELATIONSHIP BETWEEN ROBOT POSTURE AND MANIPULABILITY

This study focused on six degrees-of-freedom industrial robots. Robot motion can be represented in two ways: as a set of end effector position/posture \( \mathbf{r} \), or as a set of each joint angle \( \mathbf{q} \). These approaches are represented by Eqs. (1) and (2), respectively, as follows:

\[
\mathbf{r} = [P_x \ P_y \ P_z \ \phi \ \rho \ \gamma]^T \tag{1}
\]
\[
\mathbf{q} = [	heta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5 \ \theta_6]^T \tag{2}
\]

The forward kinematics for obtaining \( \mathbf{r} \) from \( \mathbf{q} \) are expressed by Eq. (3), while the inverse kinematics for obtaining \( \mathbf{q} \) from \( \mathbf{r} \) are expressed by Eq. (4).

\[
\mathbf{r} = f(\mathbf{q}) \tag{3}
\]
\[
\mathbf{q} = f^{-1}(\mathbf{r}) \tag{4}
\]

By differentiating Eq. (3) with respect to time, Eq. (5) is obtained as follows:
The manipulability \( w \) is calculated by using the Jacobian matrix \( J(q) \) of Eq. (5), as follows:

\[
    w = \frac{1}{\det(J(q)J(q)^T)}
\]

The value range of the manipulability \( w \) is \( w > 0 \), and the posture of the robot corresponds to \( w = 0 \), which means singularity.

**DETERMINATION OF TOOL LOCATION**

Figure 1 shows the determination of tool location in a polishing operation by using a rotational tool. At first, the sets of point C and vectors \( N, F \) are generated on the target shape on the basis of 3D computer aided design (CAD) data. Point C is the contact point on the target workpiece. Vector \( N \) is the unit normal vector at C. Vector \( F \) corresponds to the tool feed direction. The tool center point P is a point offset in the \( N \) direction by the tool radius. The direction of the tool posture vector \( T \) is the same as that of \( N \). The tool direction vector \( D \) is the vector product of \( F \) and \( N \). Each end effector position/posture \( r \) is determined by the \( P, T, \) and \( D \) of each contact point.

In cases where the operations use a non-rotational tool, such as the sealing and welding shown in Fig. 2, the tool directions at each contact point can be determined arbitrarily as the robot performs the task. In this study, we considered that the safe performance of the task is important, and propose a method of selecting a suitable tool posture with maximum manipulability from all possible postures.

In the case of determining the tool posture without limiting the tool direction, as shown in Fig. 3, the tool posture vector \( T \) and tool direction vector \( D \) are regarded as the initial vectors \( T_0 \) and \( D_0 \), respectively. Next, vectors \( D_n (n = 1, 2, \ldots, N) \) are generated by rotating \( D_0 \) around \( T_0 \) at constant angular intervals.

Then, the vectors \( T_m (m = 1, 2, \ldots, M) \) are generated by rotating \( T_0 \) around \( D_n \) at constant angular intervals, as shown in Fig. 4.

The end effector position/posture \( r_{mn} \) is calculated from the set of \( T_{mn} \) and \( D_{mn} \) by using Eq. (1). Additionally, the joint angles \( q_{mn} \) are calculated by solving the inverse kinematics of Eq. (4). The manipulabilities \( w_{mn} \) corresponding to each \( r_{mn} \) are calculated by Eqs. (5) and (6), and \( q_{mn} \). The set of \( T_{mn} \) and \( D_{mn} \) corresponding to the maximum value of manipulability \( w_{\text{max}} \) is selected from all of the calculated \( w_{mn} \) values.

The optimal robot motion, where the manipulability will become maximum, can be obtained at each contact point by applying the process described above.

**OPTIMIZATION OF WORKPIECE PLACEMENT**

We propose an optimization method of workpiece placement based on the response surface methodology, which is an optimization technique [8]. The objective of the response surface methodology is to obtain the continuous surface (response surface) by approximating the discrete response data (objective variables) influenced by various factors (explanatory variables).
Parameter setting for workpiece placement

In this study, the explanatory and objective variable correspond to the workpiece placement $p$ and the summation of manipulability $W$, respectively. $p$ represents the vector expressed by Eq. (7), as follows:

$$p = [r_w \ \theta_w \ \phi_w \ \omega_w \ \rho_w \ \gamma_w]^T$$  \hspace{1cm} (7)

Here, $r_w$, $\theta_w$, and $\phi_w$ represent the position $O_w$ in the machine coordinate system of the robot by using a polar coordinate system, as shown in Fig. 5, which corresponds to the origin of the workpiece coordinate system. Additionally, $\omega_w$, $\rho_w$, and $\gamma_w$ are the rotational angles around the $x$, $y$, and $z$ axes, respectively, and are used to determine the posture in the workpiece coordinate system, as shown in Fig. 6.

Next, the searching space of workpiece placement is defined. The ranges of each element of $p$ are defined by following Eqs. (8), (9), and (10).

$$r_{\text{min}} \leq r \leq r_{\text{max}}$$  \hspace{1cm} (8)

$$0 \leq \theta_w, \gamma_w \leq \pi$$  \hspace{1cm} (9)

$$-\pi \leq \phi_w, \omega_w, \rho_w \leq \pi$$  \hspace{1cm} (10)

Here, the values of $r_{\text{min}}$ and $r_{\text{max}}$ are determined on the basis of the robot’s movable range and workpiece size.

Generation of discrete data

The searching space of the workpiece placement $p$ should be represented as a six-dimensional space, where one point in the space corresponds only to one workpiece placement. The data required for the generation of the response surface can be obtained by dividing the searching space.

In the case where the space is divided into $N$ blocks, as shown in Fig. 7, robot programs are made for each workpiece placement $p_i (i=1, 2, \ldots, N)$ corresponding to the center point of each block. The summation of manipulability $W_i$ is calculated from each robot program and the obtained sets of $(p_i, W_i)$ are used to generate the response surface. The abovementioned processing is performed in six-dimensional space; thereby, the required discrete data can be obtained.

Response surface setting

The response surface is generated by the $L$-order polynomial approximation of the obtained discrete data, and Eq. (11) can be obtained as follows:

$$f(p) = a_0 + \sum_{l=1}^{L} a_{1l} r_w^l + \sum_{l=1}^{L} a_{2l+1} \theta_w^l + \sum_{l=1}^{L} a_{3l+2} \phi_w^l + \sum_{l=1}^{L} a_{4l+3} \omega_w^l + \sum_{l=1}^{L} a_{5l+4} \rho_w^l + \sum_{l=1}^{L} a_{6l+5} \gamma_w^l$$  \hspace{1cm} (11)

where, vector $W$ is a summation set of manipulability $W_i$ and $W = [W_1 \ W_2 \ \cdots \ W_N]^T$; matrix $A$ is the undetermined coefficient matrix in matrix $X$, and $A = [a_{00} \ a_{11} \ \cdots \ a_{6L}]^T$; vector $E$ is a set of the error or noise observed in $W_i$. Finally, matrix $X$ is represented by Eq. (13), as follows:

$$W = XA + E$$  \hspace{1cm} (12)
Moreover, each column of $X$ is represented by Eq. (14) as a power set of each explanatory variable, as follows:

$$
R_{wi} = [r_{wi} \ r_{wi}^2 \ \cdots \ r_{wi}^L]
$$

$$
\theta_{wi} = [\theta_{wi} \ \theta_{wi}^2 \ \cdots \ \theta_{wi}^L]
$$

$$
\phi_{wi} = [\phi_{wi} \ \phi_{wi}^2 \ \cdots \ \phi_{wi}^L]
$$

$$
\omega_{wi} = [\omega_{wi} \ \omega_{wi}^2 \ \cdots \ \omega_{wi}^L]
$$

$$
\rho_{wi} = [\rho_{wi} \ \rho_{wi}^2 \ \cdots \ \rho_{wi}^L]
$$

$$
Y_{wi} = [Y_{wi} \ Y_{wi}^2 \ \cdots \ Y_{wi}^L]
$$

(14)

According to the definition of the least-squares method, the undetermined coefficient matrix $A$ can be calculated by Eq. (15), as follows:

$$
A = X^+ W
$$

(15)

where, $X^+$ is the pseudo-inverse matrix of $X$ [9].

**Optimal model selection**

In this study, the adjusted square of $R (R^2)$ was used as the measure of goodness for the model fitting. On the basis of $R^2$, the optimal model was selected from each model obtained by Eq. (12). $R^2$ was calculated by Eq. (16), as follows:

$$
R^2 = 1 - \frac{\sum_{l=1}^{N}(W_l - \bar{W})^2}{\sum_{l=1}^{N}(W_l - \bar{W})^2 N - 6L - 1}
$$

(16)

where $\bar{W}$ is the average of each element of $W$, and $\bar{W}_l$ is obtained by substituting $p_l$ into each model obtained by Eq. (12).

The model corresponding to the maximum value of $R^2$ is selected by calculating the $R^2$ of each L-order polynomial model. In this study, the $p$ that maximizes the selected model was regarded as the optimal workpiece placement.

**VERIFICATION EXPERIMENT USING ACTUAL ROBOT**

**Target shape**

To confirm the effectiveness of the proposed methods, a verification experiment was conducted by applying the proposed methods to a sealing process.

The target workpiece was modeled as the rear window of a car, as shown in Fig. 8(a). The target path was created by shifting the outline of the target surface towards the interior by 30 mm. The start/end points and the tool feed direction of the sealing path are shown in Fig. 8(b), while the passing points of the sealing path are shown in Fig. 8(c). The total number of contact points was 2,793.

**Simulation of robot movement**

The best and worst placement was obtained by using the proposed workpiece placement optimization method based on the summation of manipulability at all contact points. Figures 9 and 10 show the worst and best workpiece placement, and Table 1 lists the parameters determining each placement.

The motion simulation of the worst and best placement was conducted. Figures 11 and 12 show the postures of the robot at each sealing point shown in Fig. 8(c).

In the case of the worst placement, although the tool postures at each sealing point were optimized by the proposed method, the tool posture changed suddenly between the states shown in Figs. 11(d)-(e) and 11(h)-(i). However, in the case of the best placement, the robot completed the prescribed operation without a sudden change in the tool posture, as shown in Fig. 12.

**Remarks**

Fig. 13 shows the changes in the value of manipulability ($w$) at each sealing point. The minimum value of manipulability was improved from $1.64 \times 10^8$ to $2.56 \times 10^8$ by moving the workpiece from the worst to the best placement. Moreover, the maximum value was also improved from $4.44 \times 10^8$ to $5.99 \times 10^8$. Additionally, the summation of manipulability was improved from $0.89 \times 10^{12}$ to $1.11 \times 10^{12}$. Consequently, the worst placement, which was unsuitable to the operation of the robot, and the best placement, where the robot was able to move safely, could be obtained by using the proposed method.
Table 1: Workpiece placement parameters

<table>
<thead>
<tr>
<th>Placement</th>
<th>( r_w ) [mm]</th>
<th>( \theta_w ) [deg]</th>
<th>( \phi_w ) [deg]</th>
<th>( \omega_w ) [deg]</th>
<th>( \rho_w ) [deg]</th>
<th>( \gamma_w ) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst</td>
<td>1088.4</td>
<td>47.8</td>
<td>-4.5</td>
<td>-150.0</td>
<td>90.0</td>
<td>150.9</td>
</tr>
<tr>
<td>Best</td>
<td>927.3</td>
<td>97.2</td>
<td>2.2</td>
<td>90.0</td>
<td>-150.0</td>
<td>87.9</td>
</tr>
</tbody>
</table>

Figure 9: Worst workpiece placement obtained by proposed method.

Figure 10: Best workpiece placement obtained by proposed method.

Figure 11: Robot motion in worst workpiece placement.
CONCLUSIONS

In this study, we developed functions in order to obtain the optimal robot motion during a sealing operation with consideration to manipulability. One function was the calculation of tool postures without a sudden change in the robot’s motion and passage of singularity, while the other function was the optimization of workpiece placement in order to ensure the safe movement of the robot. As a result, the following conclusions were drawn:

1. By optimizing the tool postures at each sealing point, robot motion without a sudden change and passage of singularity can be obtained.
2. By using the response surface methodology, the optimization of the workpiece placement is realized such that the robot can perform the sealing operation safely.

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REFERENCES