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Continuous path control of a 5-DOF parallel-serial hybrid robot†

Takuma Uchiyama[1,*], Hidetsugu Terada[1] and Hironori Mitsuya[2]
[1] *Graduate School of Medical and Engineering Science, University of Yamanashi, Kofu Yamanashi, Japan*
[2] *Kreuz Co.Ltd, Noda Kariya Aichi, Japan*

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Abstract

Using the 5-degree of freedom parallel-serial hybrid robot, to realize the de-burring, new forward and inverse kinematic calculation methods based on the "off-line teaching" method are proposed. This hybrid robot consists of a parallel stage section and a serial stage section. Considering this point, each section is calculated individually. And the continuous path control algorithm of this hybrid robot is proposed. To verify the usefulness, a prototype robot is tested which is controlled based on the proposed methods. This verification includes a positioning test and a pose test. The positioning test evaluates the continuous path of the tool center point. The pose test evaluates the pose on the tool center point. As the result, it is confirmed that this hybrid robot moves correctly using the proposed methods.

Keywords: 5-DOF parallel-serial hybrid robot; Off-line teaching; Inverse kinematic analysis; Continuous path control

1. Introduction

A 5-degree of freedom (DOF) parallel-serial hybrid robot is developed to automate the de-burring, as shown in Fig. 1. This hybrid robot consists of the parallel-link arm stage section and the serial-link arm stage section which arranged in series. In general, it is popular that the kind of this robot is controlled by the "direct teaching" method. However, that teaching method requires a long set-up time to generate the robot motion. Especially, in case of the teaching for the parallel-serial hybrid robot, we need a very long time for set-up. To reduce the set-up time for this hybrid robot motion, the teaching method should be changed from the "direct teaching" method into the "off-line teaching" method. In general, the off-line teaching method is based on inverse kinematic analysis. However, with this hybrid robot, it is difficult to calculate that kinematic analysis for two reasons. First, this hybrid robot has a complicated structure, and second, the general inverse kinematic analysis cannot calculate the 5-DOF spherical robot motion which lacks the 1-DOF. Therefore, a new inverse kinematic analysis method of the 5-DOF parallel-serial hybrid robot is needed.

In this paper, the structure of this hybrid robot is shown. Then, the kinematic analysis methods are proposed. Also, the continuous path control algorithm is proposed. To verify usefulness, a prototype hybrid robot is tested using the positioning accuracy and the pose accuracy.

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*Corresponding author. Tel.: +055 220 8452, Fax.: +055 200 8452
E-mail address: g08mm006@yamanashi.ac.jp

2. Geometrical model of the 5-DOF parallel-serial hybrid robot

The geometrical model of this hybrid robot is shown in Fig. 2 [1-3]. The origin point is defined as O_p. The parallel-link arm section consists of the constant vectors $\mathbf{C}_1$, $\mathbf{C}_2$, the linear motion vectors $\mathbf{L}_3$, $\mathbf{L}_4$, and the polar vectors $\mathbf{P}_5$, $\mathbf{P}_6$.

Fig. 1. 5-DOF parallel-serial hybrid robot.

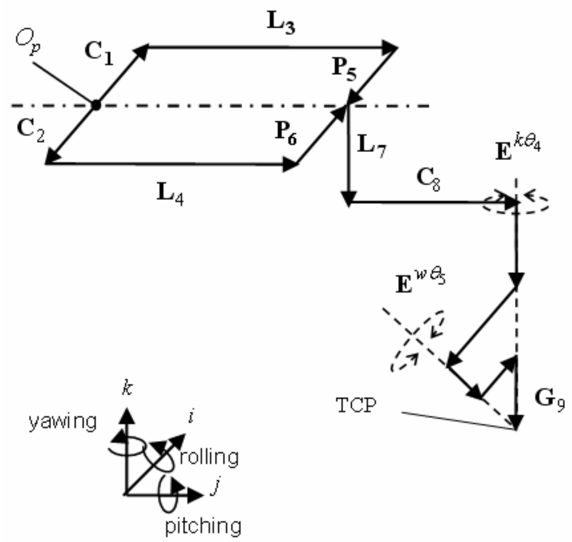

Fig. 2. Geometrical model of the 5-DOF parallel-serial hybrid robot.

The serial-link arm section consists of the linear motion vector $\mathbf{L}_7$, the constant vectors $\mathbf{C}_8$, $\mathbf{G}_9$ with the rotation θ_4 around the k-axis, and the tool center point (TCP) rotation θ_5 around the w-axis.

The position of the TCP along the i-j plane is changed by the parallel-link arm section. Also, the position of the TCP along the k-axis is changed by the serial-link arm section. The pose around the yawing direction and pitching direction is changed by the serial-link arm section. The positions and pose of the TCP are controlled individually in each section. Therefore, to calculate the kinematic analysis, we divided this hybrid robot into each section. The geometrical model of each section is defined in Fig. 3 and Fig. 4 individually. Especially, the pose of the constant vector $\mathbf{C}_8$ depends on the length of the linear motion vector $\mathbf{L}_3$ and $\mathbf{L}_4$. The position of the TCP on the i-j plane is changed by the pose of the constant vector $\mathbf{C}_8$. So, the constant vector $\mathbf{C}_8$ is included in the parallel-link arm section. At the serial-link arm section the origin point is defined as O_s.

3. Forward kinematic analysis method

The forward kinematic analysis calculates the position and pose of the TCP for this hybrid robot [3]. At this analysis, each length of the motion vectors $\mathbf{L}_3$,$\mathbf{L}_4$ and $\mathbf{L}_7$ is defined as l_3,l_4 and l_7. At the parallel-link arm section, the pose around k-axis is changed by the difference in length of l_3 and l_4. This pose is defined as the rotation θ_1. At the serial-link arm section, the pose is changed by the rotation angle θ_4 and θ_5. So, the pose of TCP is defined as Eq. (1) [3].

$$\mathbf{E} = \mathbf{E}^{k\theta_1}\mathbf{E}^{k\theta_4}\mathbf{E}^{\omega\theta_5}\mathbf{I} \tag{1}$$

In this equation, the $\mathbf{E}$ is the pose matrix; the vector "$\mathbf{I}$" shows the initial position of the TCP. The position of the TCP on the projected i-j plane, based on Fig. 3, can be calculated as Eq. (2).

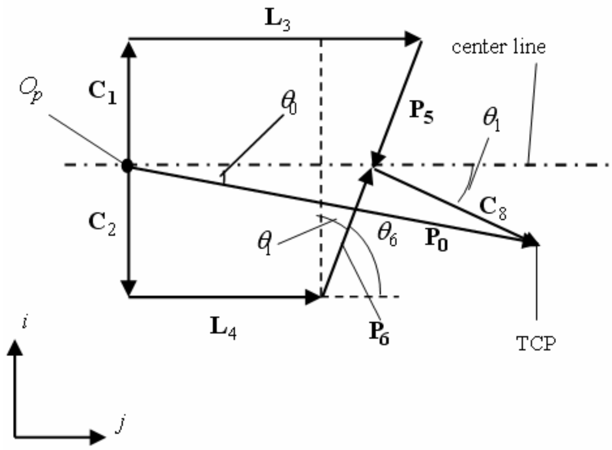

Fig. 3. Vector geometry of the parallel-link section.

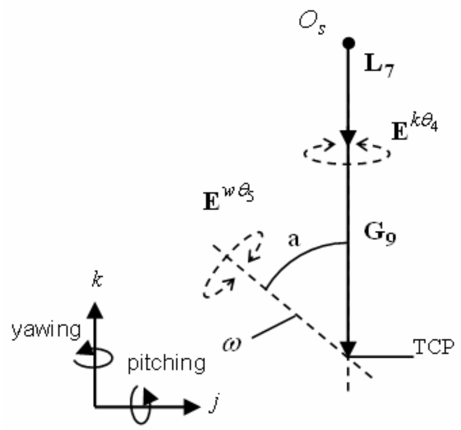

Fig. 4. Vector geometry of the serial-link section.

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} c_2 + p_6\cos\theta_6 + c_8\sin\theta_1 \\ l_4 + p_6\sin\theta_6 + c_8\cos\theta_1 \end{pmatrix} \tag{2}$$

In this equation, c_2 shows the length of the constant vector $\mathbf{C}_2$; p_6 shows the length of the polar $\mathbf{P}_6$; c_8 shows the length of the constant vector $\mathbf{C}_8$. And, the position along the k-axis, based on Fig. 4 can be calculated as Eq. (3).

$$z = l_7 + g_9 \tag{3}$$

In this equation, g_9 shows the length of the constant vector $\mathbf{G}_9$. Also, the position at the intersection of the polar vector $\mathbf{P}_5$ and $\mathbf{P}_6$ moves on the center-line as shown in Fig. 3. Therefore, θ_1, θ_6 and p_6 are shown as Eq. (4).

$$\begin{aligned} \theta_1 &= \frac{l_3 - l_4}{2c_2} \\ \theta_6 &= \frac{\pi}{2} - \theta_1 \\ p_6 &= \frac{c_2}{\cos\theta_1} \end{aligned} \tag{4}$$

4. Inverse kinematic analysis method

The inverse kinematic analysis calculates the length of each link and rotation angle from the position and pose of the TCP [3].

At first, to calculate the rotation angle θ_5 and θ_1+θ_4, the pose of TCP is defined as Eq. (5).

$$\mathbf{E} = \mathbf{E}^{k\theta_1}\mathbf{E}^{k\theta_4}\mathbf{E}^{\omega\theta_5}\mathbf{I} \tag{5}$$

To calculate the length of l_7, the position of the TCP which is along the k-axis, as shown in Fig. 4, is defined as Eq. (6). The length of l_7, based on Eq. (6), can be calculated as Eq. (7).

$$\mathbf{P} = \mathbf{L}_7^{\mathbf{k}} + \mathbf{G}_9^{\mathbf{k}} \tag{6}$$

$$l_7 = z - g_9 \tag{7}$$

The polar vector **P** shows the position of the TCP which is along the k-axis. The position of the TCP on the projected i-j plane, as shown is Fig. 3, is defined as Eq. (8). And the length of l_4, based on Eq. (7), can be calculated as Eq. (9).

$$\mathbf{P}_0 = \mathbf{C}_2 + \mathbf{L}_4 + \mathbf{P}_6 + \mathbf{C}_8 \tag{8}$$

$$l_4 = p_0 \cos\theta_0 - c_8 \cos\theta_1 + \frac{c_2 + c_8 \sin\theta_1 - p_0 \sin\theta_0}{\tan\theta_6} \tag{9}$$

The polar vector $\mathbf{P}_0$ shows the position of the TCP on the i-j plane; the p_0 shows the length of the polar vector $\mathbf{P}_0$; θ_0 shows the angle between the polar vector $\mathbf{P_0}$ and j-axis; θ_4 shows the angle between the linear motion vector $\mathbf{L_4}$ and j-axis. Also, the point at the intersection of the polar vector $\mathbf{P}_5$ and $\mathbf{P}_6$ is moved on the center-line as shown in Fig. 3. Therefore, p_0 and θ_1 are shown as Eq. (10). And, θ_0 is shown as Eq. (11).

$$\begin{aligned} p_0 &= \sqrt{x^2 + y^2} \\ \theta_0 &= \tan^{-1}\frac{x}{y} \end{aligned} \tag{10}$$

$$\theta_1 = \tan^{-1}\frac{\dfrac{y}{c_8}}{\sqrt{1 - \left(\dfrac{y}{c_8}\right)^2}} \tag{11}$$

The length of l_3, as shown in Fig. 3 is defined as Eq. (12).

$$l_3 = l_4 + 2c_2 \tan\theta_1 \tag{12}$$

The rotation angle θ_4 around the k-axis, based on Eq. (5) and Eq. (11), can be calculated.

5. Continuous path and pose control algorithms

5.1 Continuous path control

In general, the robot for de-burring needs the performance that can be moved along an arbitrary continuous spatial locus. Therefore, we investigated the continuous path control algorithm and the pose control algorithm. In this part, the continuous path control method is shown.

The equation of the position of TCP on the i-j plane is defined as the time variable function. The inverse kinematic analysis is calculated from the position of the TCP for each time. This robot is controlled, based on the length of each link and rotation angle which is calculated by the inverse kinematic analysis.

In cases in which this hybrid robot moves along the circle shape on i-j plane, the coordinate of the TCP is shown as Eq. (13).

$$\begin{aligned} x &= r\cos 2\pi t \\ y &= r\sin 2\pi t \end{aligned} \tag{13}$$

In this equation the length of "r" shows the radius; the parameter "t" shows time. To control the path continuously, the arc interpolation method is used which divides the small area. An inverse kinematic analysis is calculated from the position of the TCP for each area.

5.2 Continuous pose control

In this part, the continuous pose control method is shown. By this method, the equation of the pose of TCP is defined as the same as the position control, too. The inverse kinematic analysis is calculated from the pose of the TCP for each time. This hybrid robot is controlled, based on each rotation angle by using the similar method.

In cases in which the pose around the pitching direction is changed continuously, the pose is shown as Eq. (14).

$$\begin{aligned} \beta &= \pi t \\ \gamma &= 0 \end{aligned} \tag{14}$$

In this equation, the rotation β shows the pose around the pitching direction; the rotation γ shows the pose around the yawing direction. To control the pose continuously, the time interval is defined as a very small area. The inverse kinematic analysis is calculated from the pose of the TCP for each area.

6. Motion test

6.1 Positioning test

The positioning test evaluates the path of TCP which is drawn continuously on i-j plane. This evaluation path has a circular shape, the diameter of which is 150mm. As the result, it is confirmed that this hybrid robot draws a circle, as shown in Fig. 5(a) to (d). As the result of having measured roundness tolerance of the drawn circle, it is confirmed that the roundness tolerance of this circle is 0.8 mm. Considering the assembling error and the mechanical backlash, it is confirmed that this robot moves based on the path data of position.

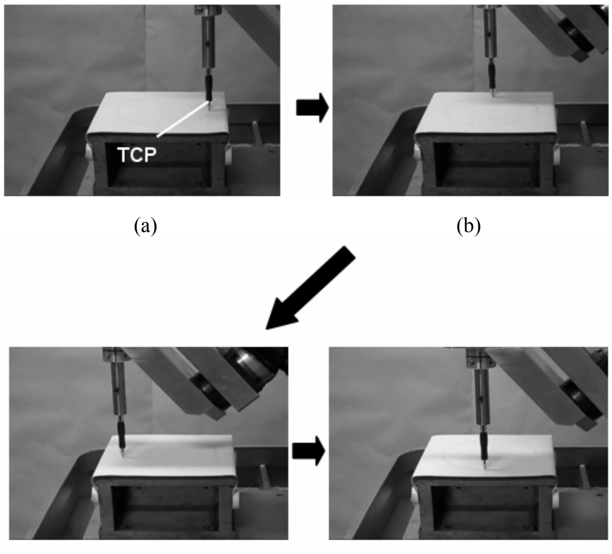

Fig. 5. Positioning test.

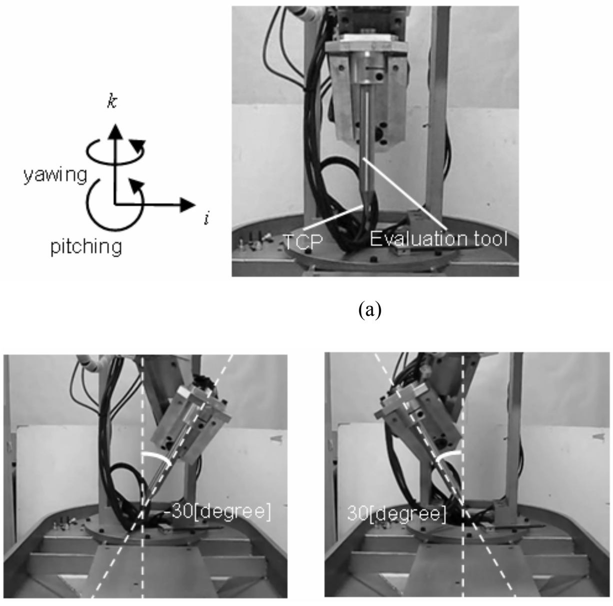

Fig. 6. Pose test.

6.2 Pose test

In the pose test, we evaluate the pose of the evaluation tool which is equipped on the TCP, as shown in Fig. 6(a). To measure the pose at the TCP, the position and the pose of the yaw yawing direction are kept constant, and only the pose of the pitching direction is changed. In this test, the pose of the yawing rotation is kept at 0 degree. And, the pose of pitching direction is changed from the -30 degree to the 30 degree continuously. As the result, it is confirmed that this robot moves to the required pose, as shown in Fig. 6(b) and (c).

7. Conclusions

Using the 5-DOF parallel-serial hybrid robot, to realize the de-burring which is based on the "off-line teaching" method, new forward and inverse kinematic calculation methods are proposed. A continuous path control algorithm, based on inverse kinematic analysis, is proposed. To verify the usefulness, a prototype robot is tested which is controlled based on the proposed methods. As the result, it is confirmed that this hybrid robot moves correctly.

In future work, to observe some errors, we will propose the calibration method of this robot.

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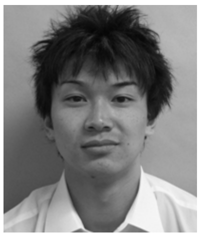

Takuma Uchiyama received his B.S. in Mechanical Engineering from the University of Yamanashi, Japan in 2004. He is currently a graduate student at the Graduate School of Medical and Engineering Science at University of Yamanashi in Kofu, Japan.

Hidetsugu Terada is currently an Associate Professor at the Graduate School of Medical and Engineering Science at University of Yamanashi in Kofu, Japan. His research interests include gear-less reducers, robotics, and micro-machining.

Hironori Mitsuya is currently an engineer at the technical development at Kreuz Co .Ltd at in Aichi, Japan.