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Energy Saving Control in Five-Axis Machine Tools Using Contouring Control*

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***Abstract*— Machine tools operate around the clock in industrial applications all over the world, and hence there is a requirement not only for high-speed and high-precision operation but also for reduced energy consumption. This paper presents a novel controller design that aims to reduce energy consumption in five-axis machine tools, which typically consist of three translational and two rotary axes. The proposed design is based on a contouring controller that has been proposed for use in high-precision machining in machine tool systems. The design also takes into consideration the relative orientation error between a tool and the workpiece in five-axis machining. The synchronous controller is also used to reduce synchronous error between two parallel actuators, which is a cause of significant mechanical damage. The experimental results demonstrate the effectiveness of the proposed controller, which reduces energy consumption by about 13 %**

I. INTRODUCTION

Machine tool control systems are generally designed so as to reduce tracking errors with respect to each individual feed drive axis. However, in workpiece machining applications, error components orthogonal to desired contour curves, called 'contour errors', are more important than tracking errors with respect to each feed drive axis.

Various methods for contouring controller design have been proposed [1]. Koren proposed a cross-coupling controller that calculates the contour error from the tracking error in each feed drive axis and reduce the contour error [2]. In addition, advanced controllers such as optimal and nonlinear controllers have been applied to contouring controller design [3]-[6]. Because both contour and tracking errors in each feed drive axis are used to calculate the control inputs in these designs, they may create some difficulties when it comes to simultaneously adjusting the controller parameters for both the contour and tracking controllers, which in turn will result in a degradation of contouring performance.

To address the tracking error problem, Lo and Chung proposed a contouring control method for biaxial feed drive systems based on coordinate transformation [7], in which the tracking errors in each feed drive axis are transformed into error components orthogonal and tangential to the desired contour curve. Because this method uses two decoupled single-input single-output systems with respect to the orthogonal and tangential directions of the contour curve, the controllers for each direction can be designed independently, thus simplifying the adjustment of the controller parameters. Chiu and Tomizuka proposed a similar approach, in which a task coordinate frame is defined at the desired position of the feed drive system, and the control system dynamics are reformulated with respect to this frame [8]. The axes of the task coordinate frame correspond to the orthogonal and tangential directions of the desired contour curve, and the orthogonal error component is regarded as an approximation of the actual contour error. Although this approach provides control system stability for any given contour curve, the difference between the actual contour error and orthogonal error component may result in a significant contour error. To compensate for the contour error caused by this difference, Peng and Chen proposed a contour index approach, in which the orthogonal error component is replaced by a newly defined error signal [9]. They also proposed a robust contouring method based on backstepping sliding mode control. Designs for five-axis machining have been presented in [10][11]. Because this coordinate transformation approach aims to reduce the error components orthogonal to the desired contour curve, it has a degree of freedom (DOF) in the direction tangential to the desired contour curve. We proposed using this DOF to reduce energy consumption [12]. Energy saving control for robotic systems are dealt with in [13] [14].

This paper presents a design for an energy-saving controller for five-axis machine tools based on the results in [11] and [12] and experimentally demonstrates the effectiveness. The flexibility to change the relative orientation between a tool and the workpiece in a five-axis machine tool offers many advantages over conventional three-dimensional machining. In this study, we present a synchronous controller that reduces energy consumption without compromising its synchronous control performance. The experimental results demonstrate the effectiveness of the proposed controller design, which reduces energy consumption by about 13 % while maintaining contouring performance.

II. CONTROLLER DESIGN

A. Contouring Control

Fig. 1 shows a typical configuration of the five-axis machine tool used in this study. In order to increase the actuation power and provide a large enough space for mounting the workpiece, some axes are driven by two actuators, such as the $Y_1 - Y_2$ axes and $A_1 - A_2$ axes in Fig. 1; thus synchronized control is required [15]. This subsection explains contouring

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control with a two-dimensional (X-Y table system) case, assuming the following dynamics:

$$M\ddot{q} + C\dot{q} = u \tag{1}$$

where $q = [x,\ y_1]^T$, $M = \text{diag}\{m_x,\ m_y\}$, $C = \text{diag}\{c_x,\ c_y\}$ and $u = [u_x,\ u_y]^T$ are the position of the feed drive system, mass matrix, viscous coefficient matrix and control input vector consisting of each axial element, respectively.

In machining, it is not necessary to reduce tracking errors for each individual feed drive axis. However, contour error is important because it relates directly to the shape of the machined part, and thus the proposed contouring control system has a DOF in the direction tangential to the contour curve. We exploit this DOF to reduce energy consumption. By reducing the control bandwidth in the tangential direction, we can reduce the control input variance, and hence consumed energy can be reduced as well.

Fig. 2 schematically explains the relation between the tracking error on each feed drive axis and the contour error. Coordinate frame Σ_w, whose axes X and Y_1 correspond to the feed drive axes, is a fixed frame. Curve c is the desired contour curve of the point of a machined part driven by the feed drive. Symbol $r = [r_x,\ r_y]^T$ is the desired position of the point of the machined part at time t and is defined in Σ_w. The actual position of the feed drive q is also defined in Σ_w. Tracking error vector e_w, which consists of the tracking error on each feed drive axis, is defined as follows:

$$e_w = [e_{w1},\ e_{w2}]^T = q - r. \tag{2}$$

Feed drives are generally controlled to reduce the magnitude of e_w by activating each feed drive axis independently. e_c is the contour error, which is defined as the minimum distance between q and r_a, which is the closest point from q to desired curve c. Contour error e_c, rather than tracking error e_w, should be reduced in machining, because e_c relates directly to the shape of the machined part. In other words, if e_c is reduced to zero, the desired machined part shape can be realised even when error e_w remains.

However, if curve c has a complex shape, it is difficult to obtain the value of e_c in real time. To obtain the approximate value of e_c, it has been proposed that the local coordinate frame Σ_l be defined as shown in Fig. 2 (e.g., [8]). The origin of Σ_l is at r and the axes are $l_i (i = 1, 2)$. Axis l_1 is in the tangential direction of c at r, while the direction of l_2 is perpendicular to l_1. Error vector e_w is expressed with respect to Σ_l as follows:

$$e_l = [e_{l1},\ e_{l2}]^T = R^T e_w,\ R = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}. \tag{3}$$

where θ is the inclination of Σ_l to Σ_w as shown in Fig. 2.

In this approach, error e_{l2} is regarded as an estimate of e_c and is reduced to improve contouring performance. This approach has advantages in that the contouring controller can be designed without a need to acquire the actual contour error e_c and the tracking performance along l_1 and l_2 can be adjusted independently. If, however, $|e_{l1}|$ is significant, there

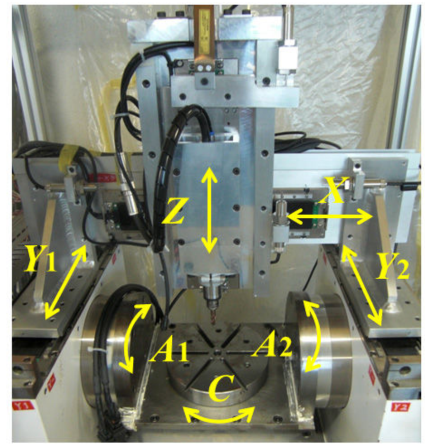

Fig. 1. Five-axis machine tool and axis definitions

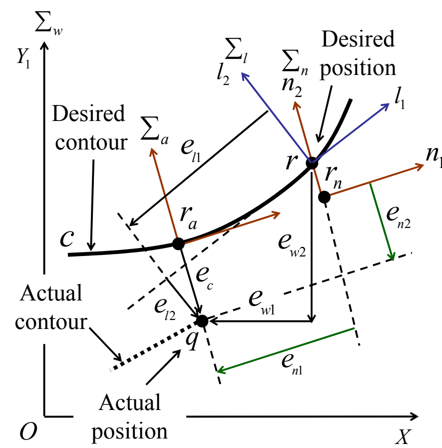

Fig. 2. Definitions of tracking errors

may be a difference between e_c and e_{l2} that is not negligible. If $|e_{l1}|$ is reduced to avoid this, however, then there is little advantage over the conventional control system, which aims to reduce both e_{w1} and e_{w2}.

We propose using a generating coordinate frame Σ_n, as shown in Fig. 2, to reduce the difference between the actual and the approximate contour error in a manner similar to that in [12]. This approach is called 'reference adjustment'. Error e_{n1} and e_{n2} are independently reduced in this design. Error e_{n2} is used as an estimate of contour error e_c. We generate frame Σ_n as follows:

Assuming that the desired velocity along the segment between the desired position r and a position r_a, which is the nearest position of the desired curve c to q, is nearly constant, time t_d required to pass through this segment is estimated as follows:

$$t_d = -e_{l1}/\sqrt{\dot{r}_x^2 + \dot{r}_y^2}. \tag{4}$$

Origin r_a and inclination θ_a of frame Σ_a in Fig. 2, which is at the position nearest to q on the desired contour curve, is estimated as follows:

$$\hat{r}_a = r(t-t_d),\ \hat{\theta}_a = \theta(t-t_d), \tag{5}$$

where $\hat{r}_a$ and $\hat{\theta}_a$ are estimates of r_a and θ_a, respectively. $r(\ )$ and $\theta(\ )$ denote functions of time. The modified desired position r_n is represented from Fig. 2 as:

$$r_n = r + Q(\hat{r}_a - r), \tag{6}$$
$$Q = \hat{R}_a S \hat{R}_a^T,\ S = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}.$$

where $\hat{R}_a$ is an approximation of a rotation matrix at Σ_a. Matrix $\hat{R}_a$ is obtained by replacing θ in R in Eq. (3) with $\hat{\theta}_a$. Derivatives of r_n are obtained as follows:

$$\dot{r}_n = \dot{r} + \dot{Q}(\hat{r}_a - r) + Q(\dot{\hat{r}}_a - \dot{r}), \tag{7}$$
$$\ddot{r}_n = \ddot{r} + \ddot{Q}(\hat{r}_a - r) + 2\dot{Q}(\dot{\hat{r}}_a - \dot{r}) + Q(\ddot{\hat{r}}_a - \ddot{r}). \tag{8}$$

Based on the above calculation and Eq. (1), the following control input equation is considered:

$$u = M\{\ddot{r}_n - \hat{R}_a(K_{vl}\dot{e}_n + K_{pl}e_n) - \ddot{\hat{\theta}}_a I_e e_{wn} + \dot{\hat{\theta}}_a^2 I e_{wn} - 2\dot{\hat{\theta}}_a I_e \dot{e}_{wn}\} + C\dot{q}, \tag{9}$$
$$I_e = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix},$$

where $e_{wn} = q - r_n$ and $e_n = [e_{n1},\ e_{n2}]^T = \hat{R}_a^T e_{wn}$. The following control system dynamics are obtained, and the convergence speed of e_{n1} and e_{n2} is adjusted independently:

$$\ddot{e}_n + K_{vl}\dot{e}_n + K_{pl}e_n = 0. \tag{10}$$

The controller reduces the difference between actual contour error e_c and its approximation e_{n2}. Assuming that K_{vl} =diag$\{2\omega_i\}$ and K_{pl} =diag$\{\omega_i^2\}, (i = 1, 2)$, we can assign a different control bandwidth ω_i for directions tangential and normal to the desired contour curve. This approach can be naturally extended to a three dimensional case, in which tracking error components in directions normal and binormal to the desired contour curve are considered as contour errors [12].

B. Contouring controller design for five-axis machining

In five-axis machining, not only positional contour error, as shown in Fig. 2, but also tool-workpiece relative orientation error (hereafter, tool orientation error) must be considered. As shown in Fig. 3, the orientation error vector is predicted by transforming the tracking error to obtain the vector normal to the reference trajectory as follows [10]:

$$\varepsilon_o = \begin{bmatrix} \varepsilon_{oi} \\ \varepsilon_{oj} \\ \varepsilon_{ok} \end{bmatrix} = e_o - \frac{\omega}{|\omega|}\frac{e_o \cdot \omega}{|\omega|}. \tag{11}$$

where $\omega = [\omega_i,\ \omega_j,\ \omega_k]^T$ is the desired angular velocity, $O(t)$ and $O_{act}(t)$ are the desired and actual tool orientations, respectively, and $e_o = O(t) - O_{act}(t)$ is the tool orientation tracking error. By using normalised angular velocity, $\bar{\omega} = \omega/|\omega|$, we can rewrite Eq. (11) as:

$$\varepsilon_o = e_o - \bar{\omega}(e_o \cdot \bar{\omega}). \tag{12}$$

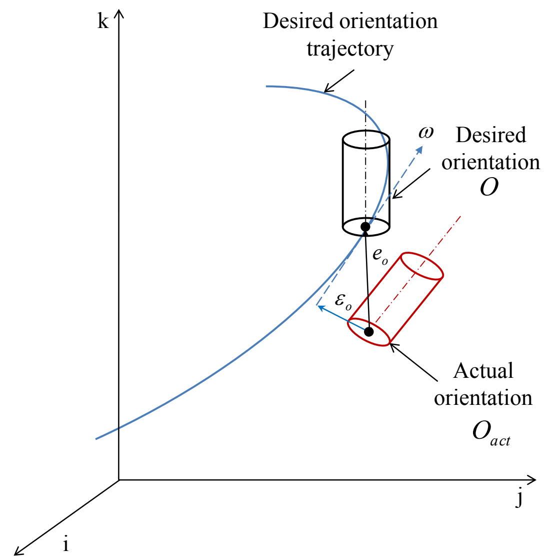

Fig. 3. Definition of tool orientation error

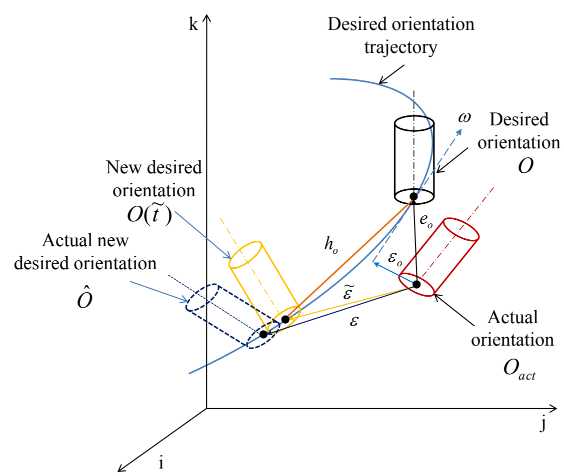

Fig. 4. Proposed transformation of tool orientation error

A disadvantage of this definition of tool orientation error is that it does not provide a true representation of machining precision because it does not take into account positional contour error. In other words, the positional contour error and the tool orientation error control loops run independently. To address this problem, we propose a new definition of the tool orientation contour error to take into consideration the synchronisation between the tool position and orientation. In the proposed approach, it is assumed that the tangential error component is larger than the normal and bi-normal components. The rotary drives in five-axis machines attempt to eliminate the tool orientation tracking error e_o and the deviation in the normal direction, ε_o, from the desired orientation trajectory, as shown in Fig. 3. An overcut or undercut is caused by a mismatch between the desired tool orientation O and the delayed desired orientation $\hat{O}$ as shown in Fig. 4, which corresponds to a point on the reference trajectory c nearest to the actual position q in Fig. 2. In order to prevent this mismatch, the rotary drive axis must use a control scheme to reduce the actual tool orientation contour error ε, which is defined as the difference between the actual orientation O_{act} and the delayed desired orientation $\hat{O}$.

Because it is a time consuming task to calculate the actual tool orientation contour error ε in real time, an approximation of ε can be estimated by the error vector $\tilde{\varepsilon} = [\tilde{\varepsilon}_i, \tilde{\varepsilon}_j, \tilde{\varepsilon}_k]^T$, defined as follows:

$$\tilde{\varepsilon} = O(\tilde{t}) - O_{act}(t), \ \tilde{t} = t - t_d. \tag{13}$$

where $O_{act}(t)$ and $O(\tilde{t})$ are the actual, and new desired reference tool orientations, respectively, as shown in Fig. 4. This orientation error can be expressed in the tool-coordinate system Σ_W as follows:

$$\tilde{e} = \left[\begin{array}{cc} \tilde{e}_a & \tilde{a}_c \end{array} \right]^T = \left[\begin{array}{c} \tilde{\theta}_a \\ \tilde{\theta}_c \end{array} \right] - \left[\begin{array}{c} \theta_{a_{act}} \\ \theta_{c_{act}} \end{array} \right]. \tag{14}$$

where $\theta_{a_{act}}$ and $\theta_{c_{act}}$ are the actual positions of the rotary drives and $\tilde{\theta}_a$ and $\tilde{\theta}_c$ are the rotary drive positions corresponding to time $\tilde{t}$. The authors verified the effectiveness of the proposed estimation method for tool orientation by means of a simulation [11].

C. Synchronization controller design

In order to increase the actuation power and to provide a large enough space for mounting the workpiece, a typical five-axis machine tool, as shown in Fig. 1, consists of driving axes with two actuators, such as the $Y_1 - Y_2$ axes and $A_1 - A_2$ axes. Hence we need to consider synchronized control as well when applying contouring control to reduce energy consumption. Assuming that the mass of the table is supported equally by two parallel axes, we have the following dynamics for the $Y_1 - Y_2$ axes:

$$m_y \ddot{y}_i + c_y \dot{y}_i = f_{yi}, \ i = 1, 2 \tag{15}$$

where y_i is the position of the Y_i axis, f_{yi} is the control input force, m_y is half of the table mass, and c_y is the viscous friction coefficient; c_y is assumed to be the same for each parallel axis.

Because even a small synchronous error between the Y_1 and Y_2 axes causes significant mechanical damage, we propose the following synchronous controller for the Y_1 and Y_2 axes:

$$f_s = -m_y(k_{vs}\dot{e}_s + k_{ps}e_s) + c_y\dot{e}_s, \tag{16}$$

where e_s is the synchronous error; $e_s = y_1 - y_2$, $f_s = f_{y1} - f_{y2}$, and k_{vs} and k_{ps} are the controller gains. From Eqs. (15) and (16), we have the following control system dynamics:

$$\ddot{e}_s + k_{vs}\dot{e}_s + k_{ps}e_s = 0. \tag{17}$$

We achieve the desired control system bandwidth ω_s for synchronous control by setting $k_{vs} = 2\omega_s$ and $k_{ps} = {\omega_s}^2$. Bandwidth ω_s for synchronous performance can be assigned independent of the tracking performance of the Y_1 axis.

III. EXPERIMENT

A. Experimental conditions

We applied the proposed method to a five-axis machine tool, as shown in Fig. 1. Linear motors and direct drive motors are employed for the translation and rotational axes, respectively, so that power transmission gears are not used in this machine tool. The dynamics parameters are shown in Table I. The rated force for each linear motor is 8 N. The rated torque for $A_1(A_2)$-axis and C-axis motors are 5 Nm and 2 Nm, respectively. The position and angles of each axis are measured by encoders with resolutions for the respective parameters as 0.1 μm and 0.4 μrad. We compared the control performance and energy consumption of the following controllers:

- (c1) Independent axial control (each axis is controlled independently with a higher control bandwidth).
- (c2) Contouring controller with a higher control bandwidth in all tangential, normal and binormal directions.
- (c3) Contouring controller with a lower control bandwidth in the tangential direction.
- (c4) Contouring controller using a reference adjustment function, with a lower control bandwidth in the tangential direction.
- (c5) Contouring controller using the reference adjustment function, with a lower control bandwidth in the tangential direction and an increase in the reference feed rate.

Because a tracking error (delay) occurs in (c4), the motion distances are different between (c1) and (c4). Therefore, to conduct a fair comparison on the energy consumed to complete the motion, we increase the reference feed rate in (c5) by 2 % on the basis of the result of a preliminary experiment. The same control bandwidth for the rotary axes is employed in all conditions. Table II shows the control bandwidth in each experimental condition.

Energy consumption was measured by using a power tester. The reference trajectory for each axis is given as follows:

$$r_x = 10\sin(2\pi t) \ \text{ mm} \tag{18}$$

$$r_y = 10\sin(2\pi t) \ \text{ mm} \tag{19}$$

$$r_z = -10\cos(2\pi t) \ \text{ mm} \tag{20}$$

Table I Dynamics parameter values

Axis	Mass, Inertia	Viscous friction coefficient
X	5.33 kg	25.18 Ns/m
Y_1, Y_2	4.54 kg	24.20 Ns/m
Z	1.72 kg	71.65 Ns/m
A_1, A_2	0.0149 kgm^2	0.100 Nms/rad
C	0.0023 kgm^2	0.022 Nms/rad

Table II Experimental conditions (control bandwidth)

rad/s	ω_x	ω_y	ω_z	ω_t	ω_n	ω_b	ω_a	ω_c
(c1)	160	160	160	-	-	-	160	120
(c2)	-	-	-	160	160	160	160	120
(c3) - (c5)	-	-	-	30	160	160	160	120

$$\theta_a = \frac{\pi}{9}\sin(2\pi t) \quad \text{rad} \tag{21}$$

$$\theta_c = \frac{\pi}{18}\sin(2\pi t) \quad \text{rad} \tag{22}$$

Fig. 5 shows a three dimensional profile of the reference trajectory. The actual contour error - i.e. the shortest distance from the position at time t to the reference trajectory - is calculated by solving an optimisation problem from the experimental data after the experiment is conducted. The actual orientation error ε can be calculated from the desired orientation.

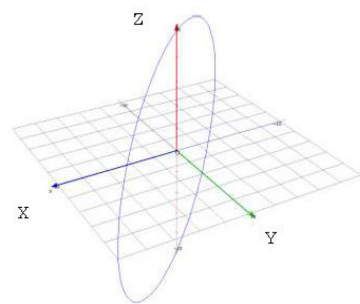

Fig. 5. Profile of reference trajectory in three dimensional space

B. Experimental results

Fig. 6 shows contour error profiles for all conditions, in which similar contouring performance is obtained except for (c3), which employs a smaller control bandwidth and does not compensate for the estimation error of contour error. Fig. 7 shows the actual tool orientation error ε in Fig. 4. Similar control performance is obtained for all conditions except (c3). The results in Figs. 6 and 7 confirm the effectiveness of the proposed controller design that enables a reduction of controller gain in the tangential direction to the desired contour curve while maintaining control performance.

Figs. 8 and 9 show the control input profiles for (c1) and (c5), respectively, in which the control input variances in (c5) are significantly reduced by reducing the controller gains in the tangential direction. We conducted five trials; one under each condition. Fig. 10 shows the summary of the energy consumed. Conditions (c3) - (c5) provide smaller energy consumption than that of the other conditions. The proposed method (condition (c5)) reduces energy consumption by 13.2 % on average compared to the conventional design (c1), while maintaining contouring and tool orientation control performances.

IV. CONCLUSIONS

This paper presented a novel contouring controller design for five-axis machine tools, which offer many advantages over three-axis machining, such as an improved machining accuracy, reduced takt time due to reduced need for retooling and a prolonged tool life due to a change in the tool orientation. The DOF in the direction tangential to the desired contour curve of the contouring controller design was employed, so as to reduce the energy consumed in

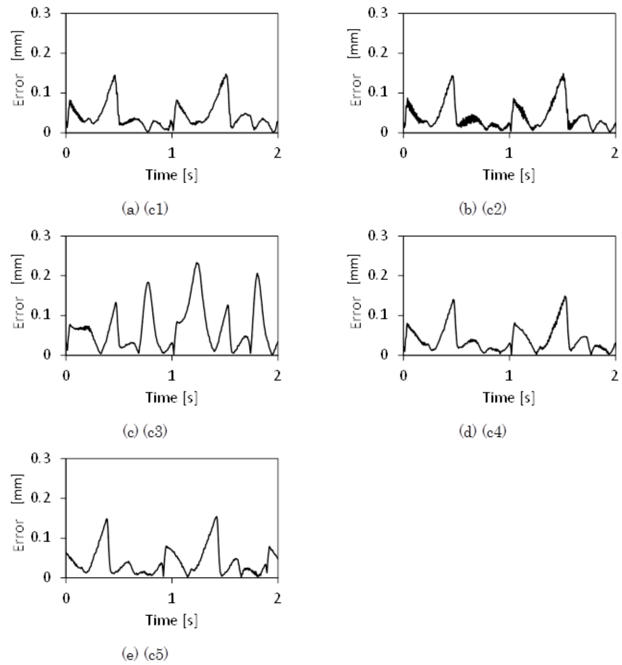

Fig. 6. Contour error profiles

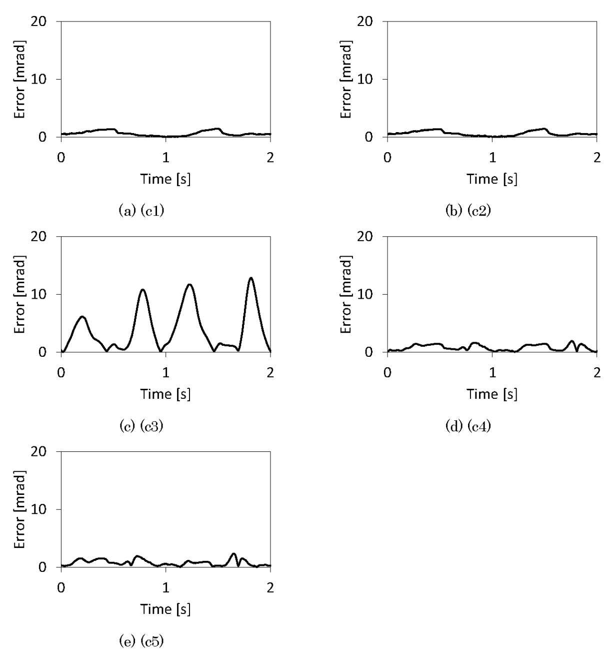

Fig. 7. Tool orientation error profiles

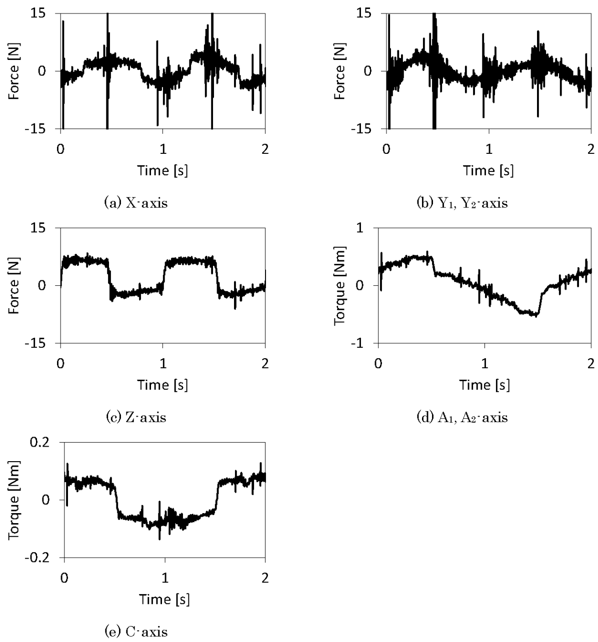

Fig. 8. Control input profiles for condition (c1)

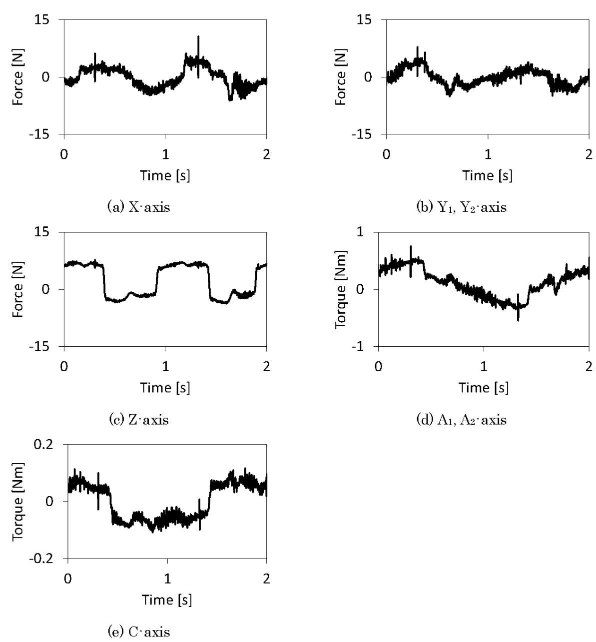

Fig. 9. Control input profiles for condition (c5)

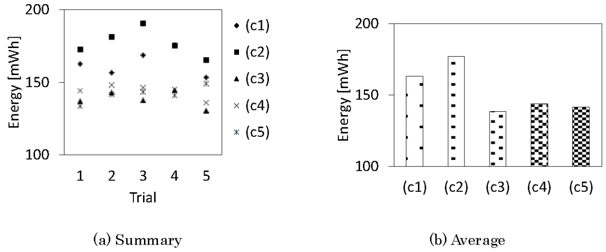

Fig. 10. Summary of energy consumed

machining. The proposed design reduced the control input variance significantly while maintaining control performance and achieved a 13.2 % reduction in energy consumption on average. Plans for future studies include applying the proposed design to actual machining, in which disturbances such as cutting forces increase control input variance. Our proposed method is expected to significantly reduce this variance and energy consumption. In addition, improving the contouring performance by including a disturbance compensator in the proposed controller is left for future work.

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