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Prediction of Actual Toolpath and Enhancement of the Toolpath Accuracy Based on Identification of Feedrate Change Characteristics of Machine Tool

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Abstract. Recently, the toolpath generation for high-speed machining of curved surfaces has become a non-trivial task. The approximated linear segments (G01-based) are widely used in commercial computer-aided manufacturing (CAM) systems. Due to the machine tool's acceleration/deceleration (Acc/Dec) control characteristics, there is a difference between the actual feed rate, the toolpath, and the commanded values when machining with CNC machine tools. This leads to the toolpath trajectory error. In addition, the cutting force applied to the cutting tool causes tool deflection. These factors cause errors between the designed and machined surfaces. In order to, therefore, predict the machined surface shape of a workpiece, it is necessary to predict the actual toolpath trajectory. The main objective of this study is to predict the actual toolpath trajectory by modeling the speed change. Furthermore, several toolpath generation methods in the postprocessing level are proposed to reduce the error between the actual toolpath and the commanded toolpath. The effectiveness and reliability of the methods are verified by experimental results.

Keywords: Acceleration/deceleration control; CAM; High-accuracy machining; NC controller; Toolpath

1. Introduction

Curved surfaces are frequently employed to represent models in various industries such as automotive manufacturing, aerospace, and mold production. With the growing demands within the manufacturing sector, there is a pressing need to enhance the precision of numerical control (NC) machining to meet these requirements (Chen *et al*., 2023; Dat, Phong, and Phuc, 2022; Tunc *et al*., 2019; Yan *et al*, 2015; Lazoglu, Manav, and Murtezaoglu, 2009; Wang, Yu, and Liao, 2006). Machining errors due to tool deflection are an essential issue in the machining process (Changqing *et al*., 2020; Ghorbani and Movahhedy, 2019; Ma *et al*., 2018; Budak *et al*., 2004). Numerous studies have been done to improve machining accuracy by solving this problem. Kasahara and Fujita analyzed the relationship among cutting conditions, shearing force, and machining accuracy using process simulation (Syaefudin, Kiswanto, and Baskoro, 2021; Fujita and Iwabe 2014; Fujita and Iwabe 2013; Kasahara *et al.,* 2012). In addition, Terai et al. proposed an index of machining error

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evaluation (Terai *et al.,* 2017). The index was only inferred via geometric analysis based on the tool's elastic deformation model. However, these methods do not consider the Acc/Dec that occurs during machine tool control. In cutting, acceleration is limited by the motor's maximum torque, and the Acc/Dec control process is performed (Otsuki, Sasahara, and Sato, 2019). Therefore, the feed rate change differs from the programmed value, which results in a discrepancy between the programmed toolpath and the actual toolpath, as shown in Figure 1(a). As a result, there are errors in the shape of the machined surface.

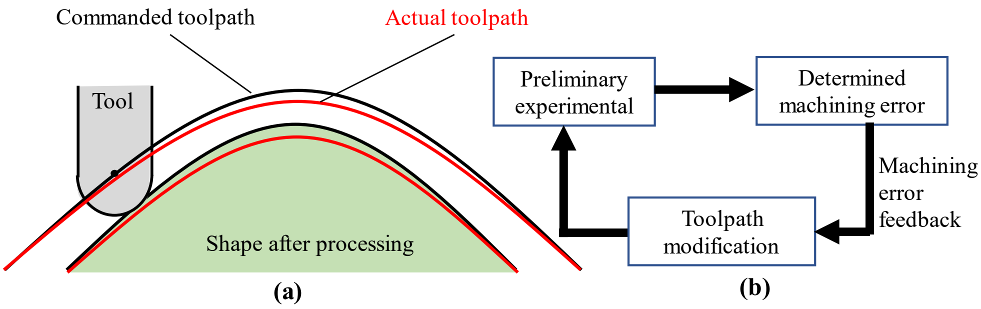


Figure 1 (a) Machined shape error; and (b) Traditional process to improve machining accuracy

Acc/Dec characteristics vary depending on the machine tool, control generation, and machining conditions like feed rate (Sulaiman *et al.,* 2022; Tapadar *et al.,* 2017; Sodemann *et al.*, 2011; Shih, Chen, and Lee, 2004; Matsubara, 2004; Schmitz and Ziegert, 2000). There are many techniques that offer some solutions to feed rate control (Yuwen *et al*., 2022; Yang and Altintas, 2015; Sencer, Ishizaki, and Shamoto, 2015; Yau and Kuo, 2001). Erdim proposed a toolpath generation method with respect to the actual volume of material being removed or to cutting forces (Erdim, Lazoglu, and Ozturk, 2006). Erkorkmaz, Rattunde and Yang presented the feed rate scheduling strategy considering the feed drive system and process mechanics (Rattunde *et al.,* 2021; Yang, Aslan, and Altintas, 2018; Erkorkmaz *et al.*, 2013). Vavruska considered the actual curvature of the toolpath for automatically optimizing the feed rate (Vavruska *et al.,* 2022). However, the Acc/Dec control process algorithm has not been clearly studied (Tang *et al*., 2022). It is still an open issue, and further study is needed (Liang, Yan, and Fang, 2022; Zhang, Li, and Guo, 2012; Yamazaki, Seto, and Tsutsumi, 2000). To mitigate shape errors and enhance machining precision, accurate prediction of machined surfaces based on predicted toolpath is imperative. Furthermore, error compensation measures must be implemented to rectify any incremental errors.

Currently, most modern machine tools are equipped with high-precision machining line control: Artificial Intelligence high-speed and high-precision contour control function of FANUC (AI function), or Geometric Intelligence (GI function) on machine tools of MAKINO. These are advanced functions that help the current commercial CNC machine system achieve the best accuracy (Figure 2). In addition to that, the correction of complex shapes and Acc/Dec adjustment in the machine tool for high speed and precision are also performed by these functions. On the other hand, almost all current generations of CNC machines use conventional control functions; the prediction of speed change and actual toolpath without AI/GI function was presented (Dat and Aoyama, 2019). In our study, toolpath prediction, measurement, and evaluation of the proposed method are performed with the AI function enabled. To the best of the authors knowledge, there are no studies conducted to better understand this new control function's Acc/Dec characteristic. Hence, studies on Acc/Dec control characteristics are necessary to improve machining accuracy.

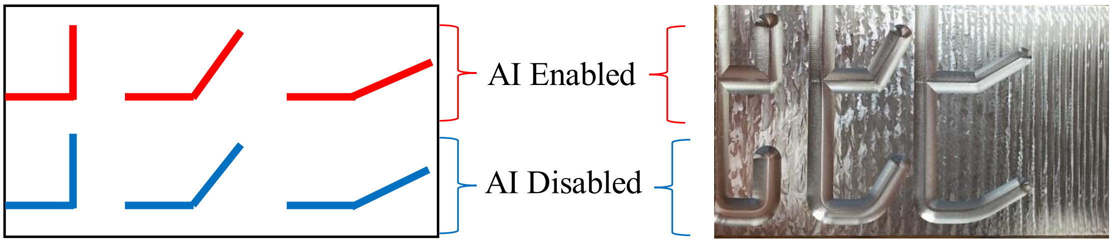


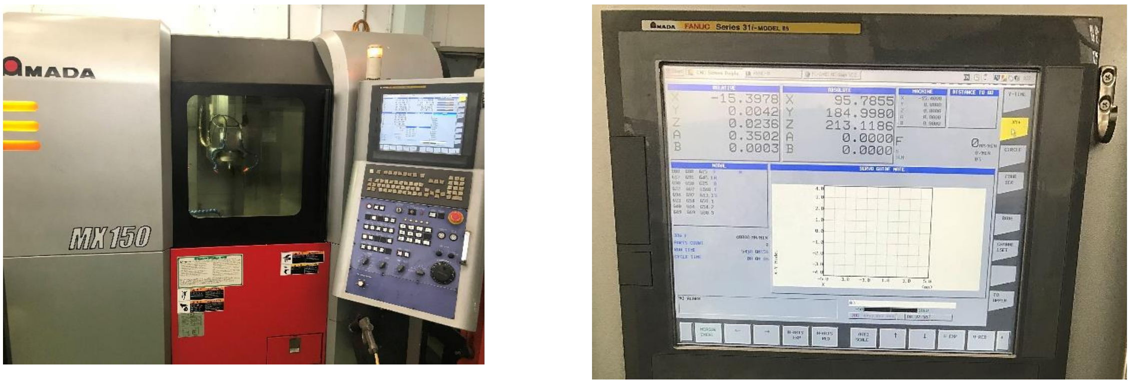
Figure 2 Comparison of machining accuracy with/without the AI control function

Throughout the above literature study, it can be concluded that there is no research considering the feed rate change to predict the actual toolpath. Accordingly, this study proposed a method to predict the actual toolpath by modeling a feed rate change with considering the Acc/Dec control of the machine tool. The predicted results are compared with the actual measurement results to prove the usefulness of the proposed model. Additionally, based on actual toolpath trajectory prediction, a new toolpath generation method is proposed to improve the toolpath accuracy by changing commanded points of the NC program in the postprocessing level (CAM system). The efficiency and reliability of this method were verified by comparison with the ideal toolpath. Our proposed method has significant advantages compared to the conventional error correction method shown in Figure 1(b).

2. Prediction method of actual feed rate and toolpath

2.1. Method of modeling the feed rate change

In this study, the machine tool used for experiments was a 5-axis CNC machine with a FANUC F31iB controller, as shown in Figure 3(a). The measurement method was performed using the FANUC Servo Guide (Figure 3b) that was integrated into the CNC machine. It is a powerful and advanced tool that allows a quick and easy measurement of servo and spindle data simultaneously for the FANUC controller.



(a) (b)

Figure 3 (a) Experimental CNC machine tool; and (b) Integrated FANUC servo guide into the machine for data acquisition

The Acc/Dec process of the machine tool involves various parameters of the machine tool controller. In this study, the feed rate was modeled by considering five set parameters of the CNC controller manufactured by FANUC. Table 1 shows the values for each parameter. These parameters are briefly described as follows. No. 1622 is the time constant of acceleration/deceleration in cutting feed for each axis. No. 1660 is the maximum allowable acceleration rate in Acc/Dec before interpolation for each axis. No, 1769 is the time constant for Acc/Dec after cutting feed interpolation in the Acc/Dec before interpolation mode. No. 1772 is the acceleration change time of bell-shaped acceleration/deceleration for look-ahead Acc/Dec before look-ahead interpolation. No. 1783 is the maximum allowable feed rate difference for feed rate determination based on corner feedrate difference. A detailed description of these parameters can be found in the FANUC Series 31i/B manual. When the high-accuracy contour control function is enabled, the feedrate is modeled using parameters No. 1783, 1660, 1772, and 1769. When the high-accuracy contour control function is disabled, the modeled feedrate is by parameter No. 1622. Based on these set parameters, the feedrate change was identified.

In the control system of the machine tool used in this study, the time constant for changing the feedrate of each control axis, as shown in Figure 5, is set as a fixed time interval without using the AI control function. It takes 64 ms before changing the feedrate to reach the target feedrate according to parameter No.1622 in the machine tool control. The feedrate model of each axis can be expressed following Equation 1.

$$v(t) = v_0 + \frac{v_1 - v_0}{64}(t - t_0) \quad (1)$$

where v_0 mm/min is the feedrate before the feedrate change, v_1 mm/min is the feedrate after the feedrate change is completed (target feedrate), t_0 is the time at which the feedrate change starts, t is the time at which the target feedrate is achieved. The unit for $(t - t_0)$ is ms.

Table 1 Values of parameters are set in the controller of the CNC machine

Parameters	No.1622	No.1660	No.1769	No.1772	No.1783
Value	64 [ms]	2600 [mm/s^2]	11 [ms]	40 [ms]	250 [mm/min]

When using the AI control function, the difference between the speed before and after the speed change is the relationship between the feedrate difference and the allowable speed difference set in the machine controller by considering No.1783 and No.1769. The actual feedrate is identified by classifying them into two cases.

(i) When the feedrate difference is less than the allowable feedrate difference (No.1783)

The machine tool controller used in this study was designed to detect the difference in feedrate ($|v_0 - v_1|$) is less than the allowable speed difference, and the time constant required for the feedrate to change from v_0 mm/min to v_1 mm/min is set to 11 ms. This feedrate difference is set to 250 mm/min according to parameter No.1783. At this time, it was assumed that the Acc/Dec when the feedrate change is constant, and the feedrate changes to the target feedrate in 11 ms according to parameter No.1769. The feedrate $v(t)$ mm/min at time t can be calculated using Equation 2 (the unit of $(t - t_0)$ is ms).

$$v(t) = v_0 + \frac{v_1 - v_0}{11}(t - t_0) \quad (2)$$

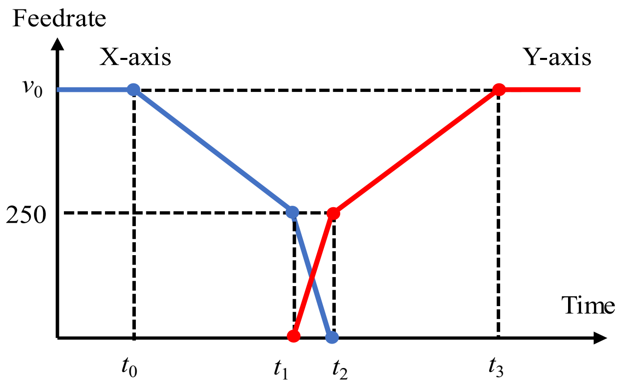


Figure 4 Schematic diagram of feed speed change of 2nd case

(ii) When the feedrate difference is greater than the allowable feedrate difference

The machine tool control unit used in this study is used to change the feedrate from v_0 mm/min to v_1 mm/min when the feedrate difference ($|v_1 - v_0|$) is greater than the allowable feedrate difference (No.1783), as shown in Figure 4. The control is carried out in two stages. In the case of the machine tool control used in this study, the allowable feedrate difference is set to 250 mm/min, as described above. In the two-stage control, in the case of deceleration control, the first stage is controlled that decelerates without generating a toolpath error (hereafter referred to as accuracy maintain control), and the second stage is a smooth simultaneous control of each axis that generates a toolpath error. Acc/Dec control (hereafter referred to as smooth movement control) is performed. In the case of acceleration control, smooth control is performed in the first stage, and accuracy maintenance control is performed in the second stage. The control decelerates on the designated toolpath without causing any toolpath error because it matches the commanded toolpath. Smooth movement control can change the toolpath smoothly, but the toolpath error occurs within the allowable value. At the time in the accuracy of maintaining control of the first stage of deceleration control, the feedrate of the control axis is decelerated until the difference between the feedrate of the control axis and the target feedrate reaches the allowable feedrate difference (No.1783). Then, at the time t_1 to t_2, the target feedrate is controlled in the smooth movement control of the second stage of the deceleration control for the X-axis. Smooth movement control is performed at the time t_1 to t_2 of the acceleration control stage for the Y-axis. The difference between the feedrate of the control Y-axis and the target feedrate is accelerated to the allowable speed difference. The accuracy is maintained and controlled up to the target feedrate at the time of the second stage of acceleration control for the Y-axis.

The procedure shown below identified the Acc/Dec time for accuracy to maintain control. When moving along the X axis and moving along the Y axis by changing the direction of movement by 90° at point C (as shown in Figure 6), the actual feedrate of the X and Y axes near point C was measured. At this time, the commanded feedrate for the X and Y axes were set from 300, to 20000 mm/min. Based on the measurement results, it was observed that the deceleration time for maintaining accuracy in the control of the X-axis depends on the commanded feedrate, while the control of the Y-axis showed similar results with acceleration time. The relationship between the commanded feedrate and the time required for accuracy maintenance control can be determined through experiments, and the accuracy maintenance control time, denoted as T ms, is calculated using the regression function (Equation 3).

$$T = 0.0062 \times v_f + 39.226 \tag{3}$$

where, v_f mm/min represents the commanded feedrate.

In this study, the smooth movement control time is set to 11 ms in the machine control according to parameter No. 1769. From the above, the feedrate difference at the time of control is greater than the allowable feedrate difference, and the feedrate in the X and Y axis directions at the time of feedrate change when decelerating the X axis and accelerating the Y axis is expressed by the following Equation 4 to Equation 9.

- when $t_0 \le t \le t_1$

$$v_x(t) = v_0 + \frac{250 - v_0}{T}(t - t_0) \tag{4}$$

$$v_y(t) = 0 \tag{5}$$

- when $t_1 \le t \le t_2$

$$v_x(t) = 250 - \frac{250}{11}(t - t_1) \tag{6}$$

$$v_y(t) = \frac{250}{11}(t - t_1) \quad (7)$$

- when $t_2 \leq t \leq t_3$

$$v_x(t) = 0 \quad (8)$$

$$v_y(t) = 250 + \frac{v_0 - 250}{T}(t - t_2) \quad (9)$$

2.2. Toolpath prediction and evaluation

The predicted toolpath was calculated based on the predicted feedrate change method. The experimental conditions were as follows: feedrate is 900 mm/min, the tool moved in the positive X-axis direction, then changed its angle by 90° at a fixed point and continued to move in the positive Y-axis direction. The actual feedrate and toolpath are measured to compare with the predicted feedrate and toolpath, respectively, and the usefulness of the proposed method was confirmed. In this study, we describe the case in which the AI control function is enabled to clarify the superiority of this control function. Simultaneously, we also describe the case in which the AI contour function is disabled to apply the proposed method for improving the accuracy in section 3.

Figure 5 shows the predicted feedrate derived from (1) and the measured feedrate without the AI control function. In Figure 5, while moving at an X-axis feedrate of 900 mm/min and a Y-axis feedrate of 0 mm/min, the moving direction is changed 90° at point A, and the X-axis feedrate is 0 mm/min and Y-axis feedrate is 900 mm/min. Point A on the blue line indicating the X-axis feedrate indicates the time when the machine reached point C (Figure 6) and the time when it started moving from point A on the red line, indicating the feedrate of the Y-axis. As shown in Figure 5, the actual feedrate of the two axes contains an undershoot error in the control. It can be recognized that both the predicted feedrate and the actual feedrate reach the target feedrate with a speed control time constant of 64 ms for both the X and Y axes. That is, considering the servo control error and recognizing that Figure 5 is in agreement, the actual feedrate at the toolpath change point when the AI function is not used can be obtained from Equation 1. The time taken for the feedrate change is approximately consistent between the predicted and measured values. It was confirmed that they could be identified. Figure 6 shows the comparison of the predicted toolpath calculated from the predicted feedrate model and the measured toolpath. It can be observed that the two toolpaths almost coincide with each other, and the error at the corner is approximately 15μm.

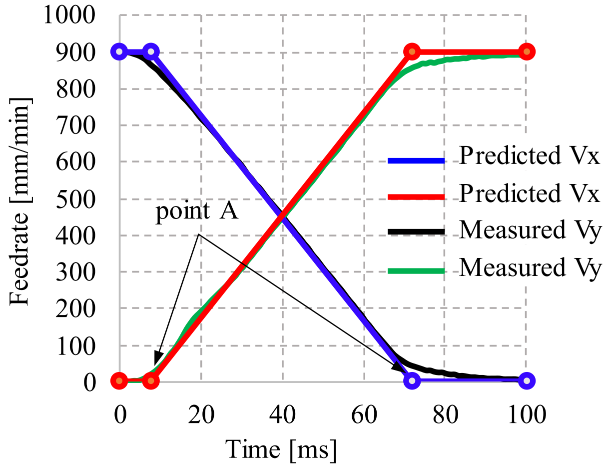


Figure 5 Comparison of predicted and measured feedrate without AI function

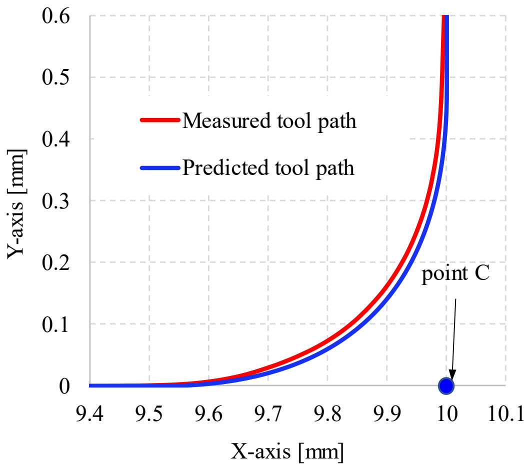


Figure 6 Comparison of predicted and measured toolpath without AI function

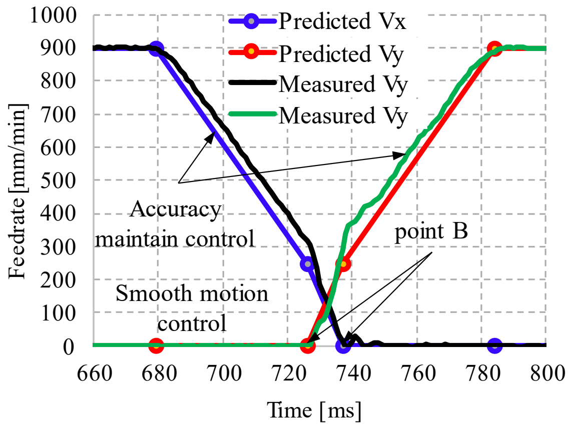


Figure 7 Comparison of predicted and measured feedrate with AI function

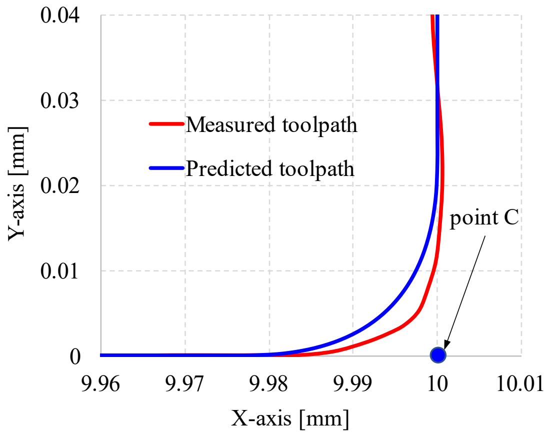


Figure 8 Comparison of predicted and measured toolpath with AI function

Figure 8 represents the predicted feedrate derived from Equation 3 to Equation 9 and the actual feedrate obtained from the experiment with the AI control function. It shows the feedrate of the X and Y axes in the vicinity of point B when the X-axis feedrate is 900 mm/min, and the Y-axis feedrate is 0 mm/min, and when the X-axis feedrate is 0 mm/min, and the Y-axis feedrate is 900 mm/min. It can be confirmed that the feedrate of each axis changes in two stages. The actual feedrate of the X and Y axes include undershoot errors in control, but both the predicted feedrate and the actual feedrate could be recognized as reaching the target feedrate with a time constant of 11 ms for feedrate control for both the

X-axis and the Y-axis. That is, by assuming that Figure 6 matches in consideration of servo control errors, it was confirmed that the actual feedrate could be identified from Equation 3 to Equation 9 when the difference in feedrate is greater than the allowable feedrate difference using an AI control function. Figure 8 shows that two toolpaths almost coincide with each other, and the prediction error at the corner is approximately 3 μm.

3. Method for improving the toolpath accuracy

Typically, as depicted in Figure 9(a), the commanded feedrate in the tool's travel direction remains constant, and the commanded toolpath consists of three points: the starting point, the corner point, and the end point. However, due to the Acc/Dec control characteristics of the machine tool controller, the resulting toolpath deviates from the original toolpath and appears as the red line shown in Figure 9(a). In this section, we present several methods to enhance the toolpath accuracy, as shown in Figure 9(a). The criterion for enhancing the machining accuracy is to align the actual toolpath as closely as possible to the commanded toolpath while minimizing any impact on the machining conditions, such as the feedrate and number of commanded points of the toolpath. Furthermore, our proposed methods aim to improve the machining accuracy even when the AI control function is not activated, as shown in Figure 9(b). This is particularly relevant for CNC machine systems that do not integrate an AI control function, which is widely used in industry.

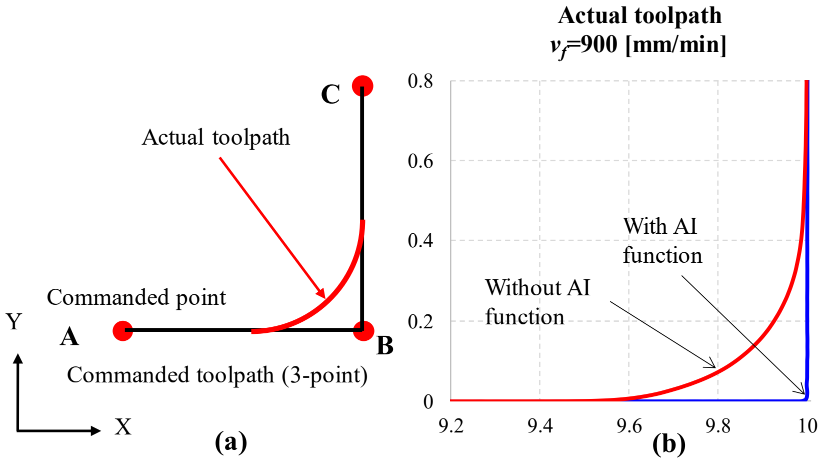


Figure 9 (a) Commanded toolpath with 3 points, and (b) comparison of contour error at the corner in case of AI control function enabled/disabled

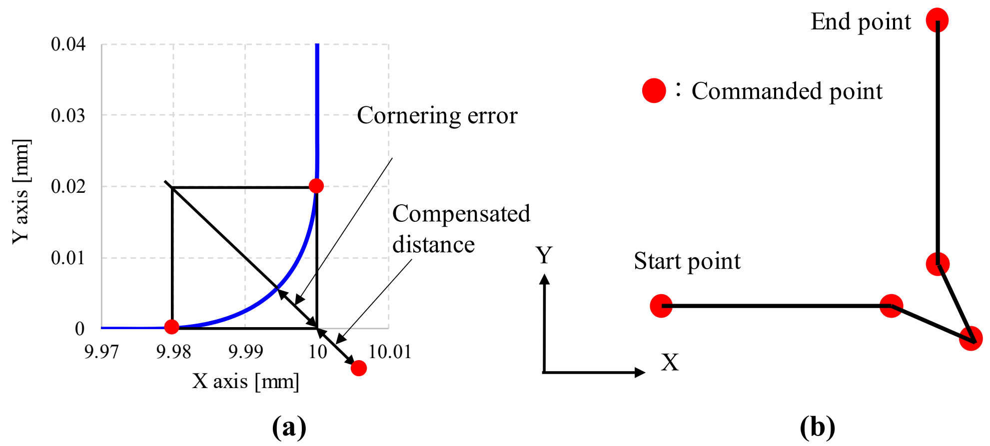


Figure 10 (a) Cornering error compensation method; and (b) Commanded toolpath with error compensation at corner

Table 2 Compensated distance of the toolpath

Methods	I	J	K	L
Compensated distance o [mm]	i	$i/2$	$i/3$	$i/4$

Based on the actual toolpath prediction model, we conducted to compensate for the error at the corner, as shown in Figure 10. In this method, the error at the corner is $\boldsymbol{i}$ [mm], and the compensated distance $\boldsymbol{o}$ [mm] of the commanded point is changed in four commanded toolpaths, as shown in Table 2. While this method has the advantage of not requiring a change in the feedrate, it is important to note that the contour error increases as a result of the abrupt change in the direction of the toolpath compared to the original toolpath.

Due to the disadvantage of the above compensation method, we proposed a new method to improve the toolpath accuracy while ensuring short machining times and small machining errors, as shown in Figure 11.

As shown in Figure 11(a), a commanded point is located in front and behind the commanded point at the corner, and the commanded feedrate between the **Q-R** points and between the **R-S** points has been changed. The distance between the commanded points $\boldsymbol{l}$ [mm] and the feedrate between the commanded points is $\boldsymbol{v}$ [mm/min], which is shown in Table 3. The result and discussion are presented in section 4.

Table 3 Commanded value for 2nd compensation method

Feedrate before and after the corner v [mm/min]	5	30	150
Distance between commanded points at the corner l [mm]	0.005	0.032	0.16

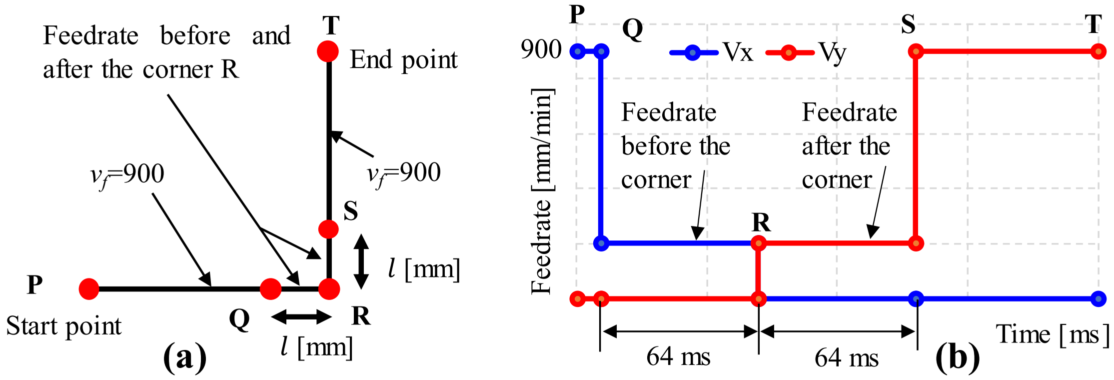


Figure 11 Method to improve the machining accuracy: (a) commanded toolpath; and (b) commanded feedrate

4. Results and Discussion

Figures 12 (a) and (b) show the measured toolpaths with different compensated distances obtained by the corner error compensation method (1st method) with and without enabling the AI control function, respectively. The compensated toolpaths are named I, J, K, and L, as shown in Table 2. These results reveal that the corner accuracy has been improved when applying the compensation method, even with or without the AI control function. However, when the AI control function is disabled, the actual toolpath is deviated quite large before and after the corner point. The maximum error is approximately 50 µm, as shown in Figure 12(b).

Based on the results of the first compensation method, it can be observed that the discrepancy between the actual toolpath and the desired toolpath is rather large. Therefore, the 2nd compensation method has been applied to improve the toolpath accuracy. The results are shown in Figure 13.

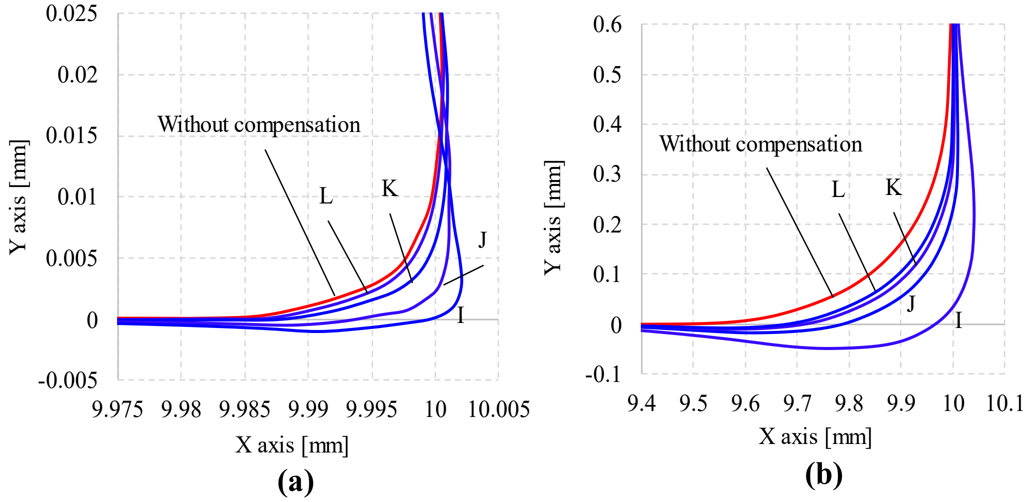


Figure 12 Results when applying the cornering error compensation method in case: (a) AI control function is enabled; and (b) AI control function is disabled

The figure displays the toolpaths obtained using the proposed method (2nd compensation method) and the conventional method, particularly when the AI control function is disabled. It can be observed that the toolpath of the proposed method is asymptotic to the commanded toolpath. The proposed method can improve machining accuracy without causing contour errors at the corner.

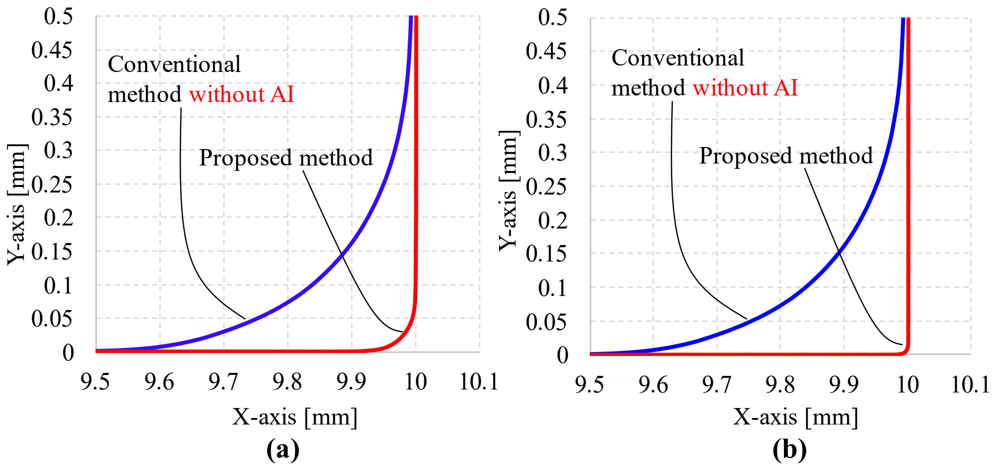


Figure 13 Experimental results with proposed method: (a) Feedrate before and after the corner v = 150 [mm/min]; and (b) Feedrate before and after the corner v = 30 [mm/min]

Especially to prove the effectiveness of the proposed method, it is compared with a three-point toolpath in the case the AI control function enabled. Figure 14 shows that the proposed method in the case of the feedrate before and after the corner of 5 mm/min is better than the conventional method (three-point toolpath) with an AI control function. Machining accuracy is improved, which is meaningful for conventional machining systems without the AI control function. Experimental results have proven the effectiveness and reliability of the proposed method.

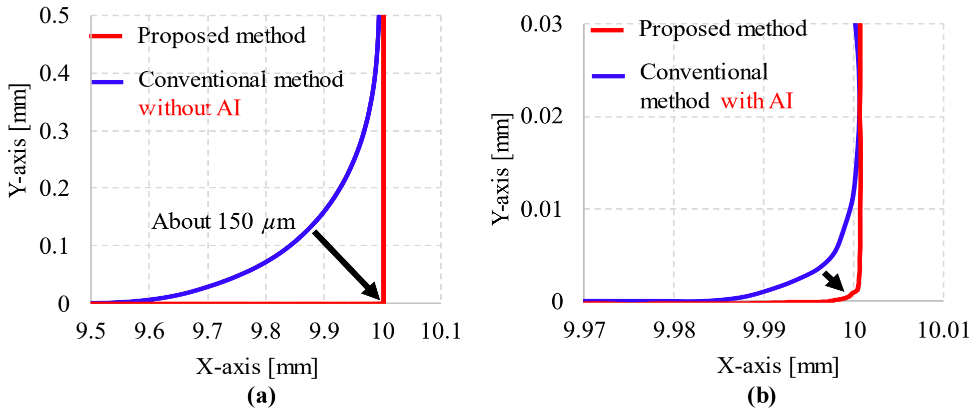


Figure 14 Experimental comparison of measured toolpaths: (a) the proposed method and conventional method (3 commanded points) without the high precision contour control; (b) the proposed method and conventional method (3 commanded points) with the high precision contour control

5. Conclusions

Based on the identification of feedrate change, this study proposed a method for predicting the actual toolpath and improving the toolpath accuracy with considering ACC/Dec control of the machine tool. In particular, the feedrate change associated with the Acc/Dec control feature of the machine tool was identified. The actual toolpath was predicted with and without enabling the high-precision contour control function. The effectiveness of the proposed method was verified by comparing the predicted and the measured toolpaths. A method for improving the toolpath accuracy at the corner points was also proposed based on the identification of feedrate change with enabling high-precision contour control. Its usefulness was confirmed by experiments. Although this study only focuses on a specific machine tool control system, the proposed approach is applicable to other machine tools for feedrate change control characteristics identification and toolpath prediction.

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