Feed Rate Control Using Fuzzy Reasoning for NC Machine Tools

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Abstract

In this paper, a 3D design and machining system based on an NC machine tool with a rotary unit is introduced to effectively produce attractive paint rollers. A post-processor is first proposed to transform a base tool path called cutter location data (CL data) to NC data, mapping the y-directional pick feed to the rotational angle of the rotary unit. The 3D machining system with the post-processor allows us to easily transcribe a relief design on a flat model surface to on a cylindrical model surface. The post-processor has another function that systematically adjusts the feed rate according to the curvature of each design to prevent the machined surface from being chipped. The post-processor generates suitable feed rate codes by using a simple fuzzy reasoning method while checking edges in relief designs. Experimental results show that wooden paint rollers with attractive relief designs can be successfully machined without any chipping.

1 Introduction

In home making industry, handy paint rollers with a simple pattern are generally used to transcribe its design to a wall just after painting. Interior planners and decorators want to use more attractive paint rollers, however, the types of the patterns are limited to several common ones. In order to efficiently provide user-oriented roller designs, a new 3D design and machining system should be considered for limited production of a wide variety of paint rollers. Up to now, although advanced 3D machining systems have been developed in various manufacturing industries [1-3], roller models with a relief design don't seem to be successfully machined at the present stage.

In this paper, a 3D design and machining system based on an NC machine tool with a rotary unit is introduced to effectively produce attractive paint rollers. The paint rollers used in general have little or no attractive design, and their designs are also limited to flat or several simple patterns. This paper addresses how to easily make attractive paint rollers with high yield rate. The most important point is that proper NC data are straightforwardly generated for the control of the rotary unit. To meet the need, a post-processor is proposed for the NC machine tool with a rotary unit. The proposed post-processor transforms a base tool path called cutter location data (CL data) to NC data, mapping the y-directional pick feed to the rotational angle of the rotary unit. The 3D machining system with the post-processor allows us to easily transcribe a relief design on a flat model surface to on a cylindrical model surface. The post-processor has another function that systematically adjusts the feed rate according to the curvature of each design to prevent the machined surface from being chipped and to shorten the cycle time for machining. The feed rate means the tangential velocity. The post-processor generates suitable feed rate codes by using a simple fuzzy reasoning method while checking edges in relief designs. Experimental results show that wooden paint rollers with attractive relief designs can be successfully carved without any chipping.

2 Post-Processor for NC Machine Tool with a Rotary Unit

In this section, an NC machine tool with a rotary unit and its post-processor are introduced to efficiently machine cylindrical models. The machined models can be used as elaborately designed paint rollers. The paint roller is very useful and convenient to directly transcribe a relief design to a wall just after painting. However, the paint rollers used in general have little or no attractive designs and also their designs are limited to flat or simple patterns. Unfortunately, even the 5-axis NC machine tools are not good at carving a relief design on a cylindrical model. To solve this problem, a post-processor is proposed for the NC machine tool with a rotary unit. The post-processor allows the NC machine tool to produce elaborately designed paint rollers. An attractive 3D design drawn on a flat model surface can be easily transcribed to a cylindrical model surface.

First of all, we introduce an NC machine tool MDX-650A provided by Roland D.G. as shown in

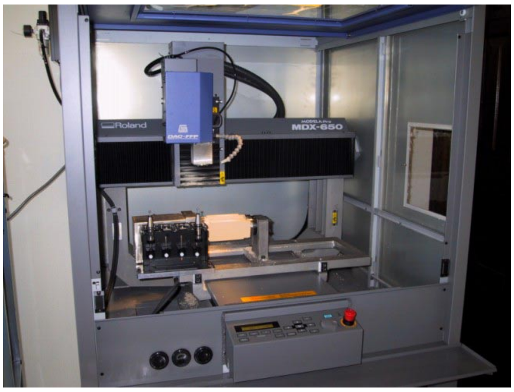

Figure 1: NC machine tool with a rotary unit.

Fig. 1. The NC machine tool equips with an auto tool changer ZAT-650 and a rotary unit ZCL-650A. The mechanical resolution of the rotary unit is about 0.0027 degrees. The NC machine tool has four degrees of freedom, i.e., three translations and one rotation. In order to provide many kinds of paint rollers with wide variety and low volume manufacturing, such a machining system that can directly carve a relief design on a cylindrical workpiece must be realized.

Next, we discuss the problem concerning the 3D machining of cylindrical shape with a relief design. When the modeling of a roller is conducted by using a 3D CAD, a base cylindrical shape is modeled in advance. Then a favorite relief design is drawn on the cylindrical model. However, the modeling of relief design on the cylindrical shape is so difficult and complicated task even if using any 3D CAD. Furthermore, its 3D machining is also more difficult even if using the 5 axis NC machine tool, in which NC data generated from the CAM are composed of x-, y-, z-, b- and c-directional components.

This paper addresses how to easily make a paint roller with an attractive relief design. The most important point is that proper NC data for the NC machine tool with a rotary unit can be generated straightforwardly. To meet the need, a post-processor is proposed to successfully transcribe the design on a flat model to on a cylindrical model. The post processor allows us to directly carve a relief design on a cylindrical workpiece. We here describe the feature of the post-processor. A desired relief design is first modeled on a flat base model. CL data are secondly generated with a zigzag path as shown in Fig. 2. In this case, the coordinate system should be set so that the pick feed direction is parallel to the table slide direction of the NC machine tool, i.e., y-direction. The proposed post-processor transforms the CL data into NC data, mapping the y-directional position to the rota-

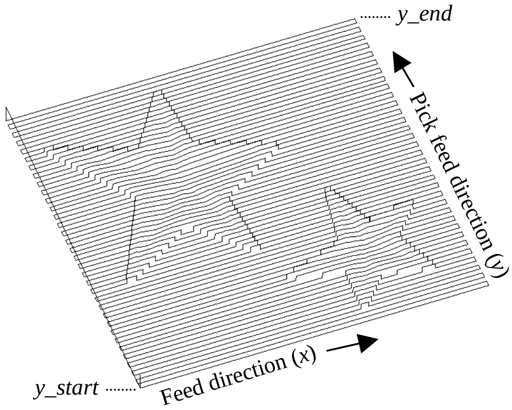

Figure 2: Example of zigzag path on a flat model.

tional angle of the rotary unit. As can be seen from the components of the NC data, when the rotary unit is active, the table slide motion in y-direction is inactive. The post-processor first checks all steps in CL data, and extracts the minimum value $y_{\_min}$ and the maximum value $y_{\_max}$ in y-direction. The angle $a(i)$ for the rotary unit is obtained from

$$a(i) = \frac{360 \times \{y(i) - y_{\_min}\}}{y_{\_length}} \quad (1)$$

where $y_{\_length}$ is the length in y-direction and is easily obtained by $y_{\_max} - y_{\_min}$. The CL data in the i-th step $[x(i)\ y(i)\ z(i)]^T$ is transformed into the NC data composed of $[x(i)\ a(i)\ z(i)]^T$ by using Eq. (1). The length in y-direction is translated into the circumference of the roller model. It is expected that the relief design shown in Fig. 2 is desirably sculptured on the surface of a cylindrical workpiece. The proposed system provides a function that easily transcribes an attractive design from on a flat model to on a cylindrical workpiece fixed to the rotary unit.

3 Feed Rate Control Using Fuzzy Reasoning

It is known that an F-code such as F3000.0 (i.e., 3000 mm/min) is generally used to set the tool's feed rate to an NC machine tool. The feed rate is one of the most important parameters to smoothly control NC machine tools and to reduce the total machining time. Although the feed rate should be set as fast as possible, if the cutter path has a large curvature or small edge then undesirable vibrations and material chipping would occur. This means that the machining accuracy tends to go down and we can't obtain the precise shape as the model designed by a 3D CAD. Especially, when a wooden paint roller with a relief design is machined, the problem of edge chipping can't be avoided. The feed rate should be suitably down so

Table 1: Consequent constants of fuzzy reasoning for $d(i)$ and $\Delta d(i)$.

c_1^A	c_2^A	c_3^A	c_4^A	c_5^A	c_6^A
$F_{\min}+0.1F_{base}$	$F_{\min}+0.2F_{base}$	$F_{\min}+0.4F_{base}$	$F_{\min}+0.6F_{base}$	$F_{\min}+0.8F_{base}$	$F_{\min}+F_{base}$
c_1^B	c_2^B	c_3^B	c_4^B	c_5^B	c_6^B
$-0.5F_{\min}$	$-0.2F_{\min}$	$-0.1F_{\min}$	$0.1F_{\min}$	$0.2F_{\min}$	$0.5F_{\min}$

that the model surface can't be damaged by the edge chipping. However, conventional post-processors don't possess the function to systematically adjust the feed rate so as to suppress the undesirable edge chipping.

The proposed post-processor has a function that automatically adjusts the feed rate according to the curvature of each model not only to shorten the total time for machining but also to keep out the edge chipping. Generally, the main-processor of CAM calculates the cutter path $\boldsymbol{p}(i) = [x(i)\ y(i)\ z(i)]^T$ with a linear approximation so that the workpiece can be machined within a tolerance to a designed model. Therefore, the larger the curvature is, the higher its point density is. Accordingly, considering the curvature results in acquiring the distance $d(i) = \|\boldsymbol{p}(i+1) - \boldsymbol{p}(i)\|$ between two adjacent steps of the CL data and its increment $\Delta d(i) = d(i+1) - d(i)$.

In this section, we propose a fuzzy feed rate generator that generates suitable feed rate codes according to $d(i)$ and $\Delta d(i)$. The fuzzy feed rate generator consists of two simple fuzzy reasoning parts whose consequent parts are constant. When the current position $\boldsymbol{X}(k) = [X(k)\ Y(k)\ Z(k)]^T$ of the end-mill at the discrete time k is $\boldsymbol{X}(k) \in [\boldsymbol{p}(i), \boldsymbol{p}(i+1)]$, the fuzzy rules are described by

Rule 1 IF $d(i)$ is $\tilde{A}_1$ THEN $F(i) = c_1^A$
Rule 2 IF $d(i)$ is $\tilde{A}_2$ THEN $F(i) = c_2^A$
⋮
Rule L IF $d(i)$ is $\tilde{A}_L$ THEN $F(i) = c_L^A$

and

Rule 1 IF $\Delta d(i)$ is $\tilde{B}_1$ THEN $\Delta F(i) = c_1^B$
Rule 2 IF $\Delta d(i)$ is $\tilde{B}_2$ THEN $\Delta F(i) = c_2^B$
⋮
Rule L IF $\Delta d(i)$ is $\tilde{B}_L$ THEN $\Delta F(i) = c_L^B$

where $\tilde{A}_j (j = 1, ..., L)$ and $\tilde{B}_j$ are the j-th antecedent fuzzy sets for two fuzzy inputs $d(i)$ and $\Delta d(i)$; c_j^A and c_j^B are respectively the consequent constants at the j-th rule for the feed rate $F(i)$ and its compensation $\Delta F(i)$; L is the fuzzy rule number. The confidence of each antecedent part at the i-th rule is obtained by

$$\omega_j^A = \mu_{Aj}\{d(i)\} \tag{2}$$

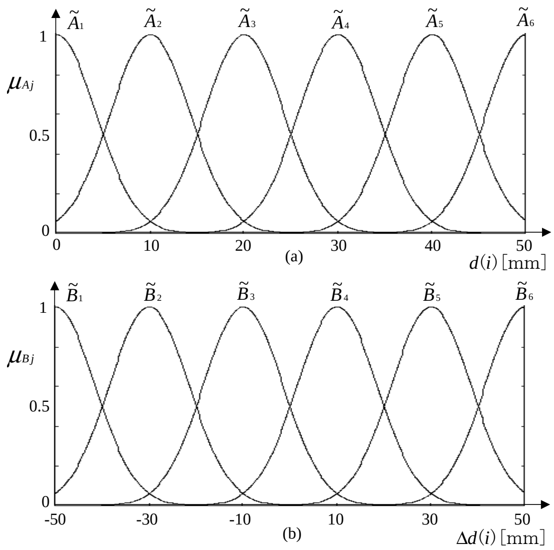

Figure 3: Antecedent membership functions.

$$\omega_j^B = \mu_{Bj}\{\Delta d(i)\} \tag{3}$$

where $\mu_X(\bullet)$ denotes the confidence of a fuzzy set labeled by X. Therefore, the fuzzy reasoning results for the feed rate and its compensation are respectively calculated by

$$F(i) = \frac{\sum_{j=1}^{L} \omega_j^A c_j^A}{\sum_{k=1}^{L} \omega_k^A} \tag{4}$$

$$\Delta F(i) = \frac{\sum_{j=1}^{L} \omega_j^B c_j^B}{\sum_{k=1}^{L} \omega_k^B} \tag{5}$$

The resultant fuzzy feed rate $\tilde{F}(i)$ is realized in the form

$$\tilde{F}(i) = F(i) + \Delta F(i) \tag{6}$$

Note that the fuzzy set used is the following Gaussian membership function

$$\mu_X(x) = \exp\{\log(0.5)(x-p)^2 q^2\} \tag{7}$$

where p is the center of membership function and q is the reciprocal value of standard deviation. Figures 3 (a) and (b) show the antecedent membership functions

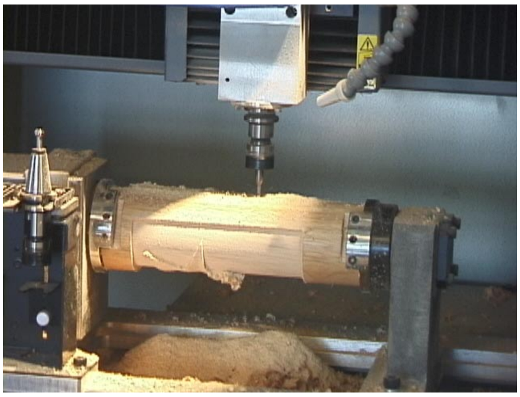

Figure 4: Carving scene of a paint roller.

designed for $d(i)$ and $\Delta d(i)$, respectively. The reciprocal values of the standard deviations are 0.2 and 0.1, respectively. The corresponding constant values in consequent parts are tabulated in Table 1, in which $F_{\max}$ and $F_{\min}$ are the maximum and minimum values for the feed rate estimated in advance; F_{base} denotes $F_{\max} - F_{\min}$. These fuzzy rules are tuned based on the experience of a skilled operator. Note that the fuzzy reasoning part yields not only larger values than $F_{\max}$ but also smaller values than $F_{\min}$ with the combination of $d(i)$ and $\Delta d(i)$.

4 Experiments

Experiments using the proposed post-processor were conducted through actual machining of cylindrical workpieces. Figure 4 shows the carving scene of a paint roller without undesirable chipping. Figure 5 shows one of the results, where the feed rate codes are generated from the fuzzy feed rate generator described in previous section. It is observed from the result that the feed rate $\tilde{F}(i)$ is suitably varied according to the curvature of the surface. Note that the periodically appeared feed rate 600 mm/min is forcibly given every pick feed motion, where the rotary unit is rotated with a small angle, e.g., 0.56 degrees. The quantity of the small angle depends on the ratio of $y_{\_length}$ to the pick feed as shown in Fig. 2. In the case of Fig. 5, the total machining time was reduced about 20% compared with the case of using a constant feed rate 600 mm/min. As can be seen, the proposed fuzzy feed rate generator provides a more intuitive and finely tunable feed rate function for post-processor.

5 Conclusions

In this paper, a post-processor using a fuzzy feed rate generator has been proposed for an NC machine tool with a rotary unit. The post-processor allowed us to easily transcribe a relief design from on a flat model to on a cylindrical workpiece. The fuzzy feed rate generator also generated suitable feed rate codes according to the curvature of the relief design, so that the total machining time could be drastically reduced without any chipping on the carved surface. Experimental results showed that attractively designed relief paint rollers could be successfully carved by using the proposed 3D machining system.

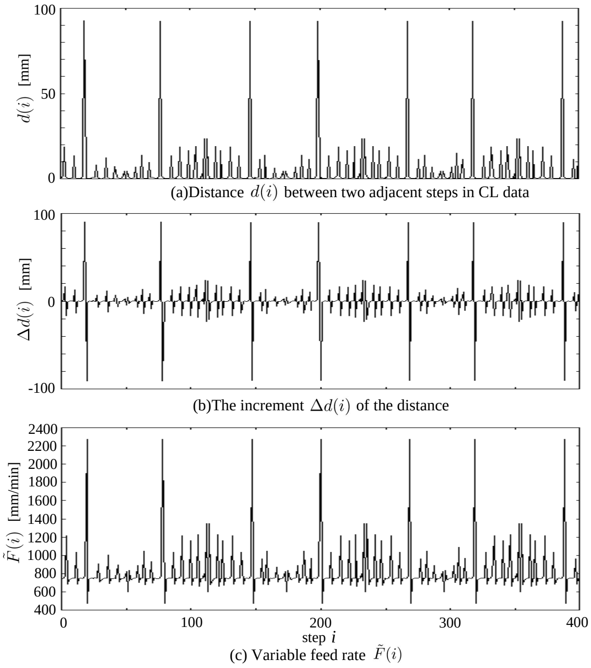

Figure 5: An example of the variable feed rate.

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