Development of an innovative autonomous machine tool for dynamic product planning

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Abstract

In the area of machining, laborsaving and automation are comparatively realized mainly by the contribution of NC machine tools so far. However, conventional NC machine tools are not autonomous and intelligent because they don’t have any feedback mechanisms during machining operations. Therefore, in order to realize dynamic product planning for an innovative autonomous machine tool, it is indispensable that machine tools have feedback mechanism to adapt cutting parameters to monitoring information. As a matter of course, it is needed for the mechanism to include a function of tool path generation in real time. Because the real time tool path generation can perform to change not only feed speed but also depth of cut during an operation. In this paper, digital copy milling system that can generate tool paths in real time is developed by applying the traditional copy milling principle. And also, machining strategy is proposed to adapt cutting parameters considering cutting load, and integrated into the digital copy milling. Feedback machining control can be realized using the digital copy milling system with the proposed machining strategy. Furthermore, in order to achieve dynamic product planning, an automatic function of product planning is added by customizing commercial CAD software. By using this automatic planning system, even in case of a cutting trouble, it is possible to reschedule product planning immediately. Autonomous machining based on dynamic product planning can enable to realize high flexibility and high durability in machining operations.

Keywords: Machining operation; Product planning; Real time tool path generation; Machining strategy; Feedback mechanism; Autonomous NC machine tool

1. Introduction

Computer numerical control (CNC) machine tools are widely used in the industry and contribute to achieve high precision, high productivity and high automatization in machining operations. However, a CNC machine tool has a common drawback that tool movement and cutting parameters (such as feed rate, spindle speed and depth of cut) are prescribed as an NC program before a real machining operation and not generally allowed to modify them during an operation. It means that product planning (both process and operation planning) is absolutely static while machining, as shown in Fig. 1. Hence, machine tools cannot avoid sudden cutting troubles such as chatter vibration and tool breakage by themselves. Therefore, product planning must be adequately prepared and verified in advance, though it requires extensive amount of time and efforts. For this reason, to realize an autonomous and intelligent CNC machine tool, which can achieve dynamic product planning, is prospected.

When it comes to dynamic operation planning, adaptive control (AC) system provides real time adjustment of the cutting parameters has been studied to improve the productivity of machining process and the quality of machined surface. These AC systems can be generally classified into two types as described below. The more successful one is adaptive control constraint type that one or more of cutting parameters are maximized within the prescribed limits of operational constraints such as maximum force, torque and power \cite{1,2}. On the other hand, the purpose of adaptive control optimization type is to enable the controller to regulate the cutting parameters by optimizing the performance index in terms of the productivity and the machining cost \cite{3,4}. There are many researchers have developed models to design machining operation control systems by employing either AC type \cite{5}.
However, in these studies CNC machine tools are essentially driven by an NC program. It means that the flexibility to adapt cutting parameters is limited because of the difficulty to change radial and axial depth of cut during a machining operation. On the other hand, in this study, NC program-less machining is assumed to achieve dynamic operation planning. And, the digital copy milling system that can generate tool paths in real time is developed, in order to change even axial and radial depth of cut during a machining operation [6].

The control principle of the digital copy milling system is quite similar to the control principle of the traditional copy milling. A tracing probe and a master model in copy milling are defined as 3D virtual models in a computer. A virtual tracing probe is simulated to follow a virtual master model, and tool motion which is corresponding to the motion of the virtual tracing probe is controlled in real time.

Also, cutting parameters are adapted by the proposed machining strategy based on machining states [7]. The machining strategy is integrated into the digital copy milling system and monitors spindle load as motor current through a CNC controller during a machining operation. NC program-less machining, which has feedback mechanism for dynamic operation planning, can be realized using the digital copy milling system with the proposed machining strategy.

In connection with automatic process planning, feature recognition is being studied with interest in this field. There are many approaches to extract meaningful machining features. For example, in the area of syntactic pattern recognition, some grammars to classify mechanical parts are devised [8,9], also in the area of graph based searching, some graphical structures to recognize machining features are proposed [10,11].

However, their studies are far from achieving dynamic process planning, because they are merely focused on the automation of planning coming before real machining. In particular, the product model is dealt with as the collection of machining features, though the removal volume should be dealt with and the workpiece model relative to the removal volume is not updated while machining.

In this study, to achieve flexible and dynamic process planning, a new approach of automatic planning is proposed. In this approach, a removal volume is obtained by subtracting a product model from a workpiece model, and both the workpiece model and the removal volume are sequentially updated during a machining operation. By using this technique and NC program-less machining mentioned above, dynamic product planning can be realized.

2. NC program-less machining

In this study, two subcomponents are developed in order to realize NC program-less machining for dynamic operation planning. The first subcomponent is a function of real time tool path generation based on the copy milling principle. It offers a flexible adaptation of cutting parameters against the conventional NC machine tool which cannot change axial or radial depth of cut instructed by an NC program. The other subcomponent is machining strategy to maintain stable cutting states during a machining operation. According to the proposed machining strategy, the cutting parameters are adapted under consideration of machining information. Dynamic operation planning, which can avoid cutting troubles and adapt cutting parameters, is indispensible to achieve autonomous machining.

2.1. Digital copy milling

In the conventional copy milling, the tool motion is controlled in real time by the motion of the tracing probe following the master model, and the control principle is simple. Therefore, the copy milling principle is applied to
control the tool motion and to generate tool paths in this study.

There are several tool path patterns such as the scanning-line mode, the contour-line mode, the characteristic-line mode, the 3D profiling mode and so on. In order to simplify the treatment of the tool motion in the digital copy milling system, the scanning-line mode for unilateral and zigzag paths and the contour-line mode are prepared as the basic tool path patterns. For both the scanning-line mode and the contour-line mode, the machining operation performs plane by plane. And, once the collision between the virtual tracing probe and the virtual master model is detected, the virtual tracing probe is controlled to follow the virtual master model, and the tool is controlled to machine the desired shape defined by the virtual master model.

In the copy milling, the feed velocity vector of the tool motion is derived from the maximum displacement detected by the tracing probe. On the other hand, the feed velocity vector of the tool motion is derived from the maximum collision between geometric models of the virtual tracing probe and the virtual master model in the digital copy milling, as shown in Fig. 2. The detection of the collision between the virtual tracing probe and the virtual master model is considered on vertical plane for the scanning-line mode, and on horizontal plane for the contour-line mode, respectively.

The displacement $\Delta d$ detected by the tracing probe is kept as the reference displacement $e_0$, and the motion of the tracing probe is controlled to follow the master model in traditional copy milling. Fig. 3 shows the relation among the vectors of the tangential feed velocity $V_T$ the normal feed velocity $V_N$ and the resultant feed velocity $V$. The tangential feed velocity $V_T$ and the normal feed velocity $V_N$ to the surface of the master model are calculated by the following equations [12]

$$|\Delta d| = |\Delta| - e_0$$  \hspace{1cm} (1)

$$|V_N| = G_N|\Delta d|$$  \hspace{1cm} (2)

$$|V_T| = V_C - G_T|\Delta d|$$  \hspace{1cm} (3)

In these equations, $\Delta d$ is the difference between the displacement $\Delta$ of the tracing probe and the reference displacement $e_0$. $G_N$ is the $V_N$ gain which defines the relation between $\Delta d$ and $V_N$, $G_T$ is the $V_T$ gain which defines the relation between $\Delta d$ and $V_T$ and $V_C$ is the commanded feed velocity, respectively.

As mentioned above, the control principle of the copy milling defined by Eqs. (1)–(3) is simple to control the motion of the tracing probe, which corresponds to the tool motion, in real time. The digital copy milling system detects the collision between the virtual tracing probe and the virtual master model, which are defined in a computer, and calculates the resultant feed velocity of the virtual tracing probe or the tool based on the control principle of the copy milling. Finally, the digital copy milling system generates the CL data (X, Y and Z code) and the F code to control an NC machine tool for every control interval time $t$.

The digital copy milling system has been developed using the Borland C++ Builder under the Microsoft Windows 2000 OS. Fig. 4(a) shows the input GUI of the digital copy milling system and an example of generated tool paths, its tool path pattern is scanning-line mode (zigzag paths), by this system. The desired machined shape, the workpiece shape, the tool property, the tool path pattern and the cutting parameters are input through the GUI.

Fig. 4(b) shows an example of generated tool paths, whose tool path pattern is the scanning-line mode (zigzag paths). It shows that not only feed speed but also axial and radial depth of cut can be changed in real time during a machining operation. The changed radial depth of cut is reflected to the next tool path line and axial depth of cut can be only reduced to avoid over load in machining. The changed axial depth of cut is reflected in a moment, and the reduction of cutting depth causes to leave the un-machined step surface, so the digital copy milling system generates additional tool paths to remove the un-machined step surface.
2.2. Machining strategy

A reasonable machining strategy, which can adapt cutting parameters to cutting states, should be established for achieving dynamic operation planning. In this study, dynamic operation planning is realized integrating the following machining strategy and the digital copy milling system.

In the machining strategy proposed, first, ‘Desired Load’ \( L_d \) to maintain suitable cutting and ‘Critical Load’ \( L_c \) to avoid cutting trouble are determined by using a cutting simulator. Furthermore, reference values such as minimum, maximum and recommended values are defined for feed rate, radial and axial depth of cut, respectively. These values are related to machining know-how and required to maintain reasonable cutting states. A recommended value is set as a default value to start the machining operation.

The flow chart of the proposed machining strategy to adapt cutting parameters and the definition of ‘Lane’ and ‘Face’ in this study are shown in Figs. 5 and 6, respectively. In the proposed machining strategy, spindle load is detected during a machining operation from a CNC controller.
as spindle motor current, and cutting parameters are adapted to the machining states. A machining operation is carried out by modifying only feed rate as far as possible. However, if feed rate becomes extremely large or small, radial depth of cut is modified. In the same way, if radial depth of cut becomes extremely large or small, axial depth of cut is modified.

In particular, in the sub-module ‘Load Watcher’, spindle load is detected at a regular interval (about 16 ms) depending on the processing interval of the CNC controller. Then, feed rate is modified when the detected spindle load becomes large or small in successive 10 intervals to avoid fluctuations of modified feed rate.

If spindle load becomes extremely large, feed rate is decreased or axial depth of cut is reduced at once in order to avoid cutting troubles. First, new feed rate $F_n$ is estimated by following Eq. (4)

$$F_n = F_p L_d / L_p$$

where $F_p$ is present feed rate and $L_p$ is present spindle load. When $F_n$ is in the range between the maximum and the minimum values, $F_n$ is adopted as feed rate. However, if $F_p$ is already extremely slow and $F_n$ becomes under the minimum value, the axial depth of cut is reduced by half.

The maximum and the average spindle load are memorized as $L_m$ and $L_a$ for every ‘Lane’ and $L_M$ and $L_A$ for every ‘Face’, respectively. In the sub-module ‘Next Lane’, an amount of modification of radial depth of cut $RD$ is decided by the ratio of $L_d$ and $L_m$ in case of decrease of $RD$, $L_d$ in case of increase of $RD$ following Eqs. (5) and (6). In the same way, axial depth of cut $AD$ will be modified for next ‘Face’ by sub-module ‘Next Face’ following Eqs. (7) and (8)

$$RD_n = RD_p L_d / L_m$$

$$RD_n = RD_p L_d / L_a$$

$$AD_n = AD_p L_d / L_M$$

$$AD_n = AD_p L_d / L_A$$

where $RD_n$ and $AD_n$ are new depths of cut, and $RD_p$ and $AD_p$ are present depths of cut.

NC program-less machining that has feedback mechanism for dynamic operation planning can be realized by the developed digital copy milling system with the machining strategy proposed here.

Table 1
Initial cutting parameters and their adapted range

| Initial parameters       | Adapted parameters (min., default, max.) |
|-------------------------|-------------------------------------------|
| Spindle speed (rpm)     | 2000                                      |
| Feed rate (mm/min)      | 200, 400, 520                             |
| Radial depth of cut (mm)| 1.0, 2.0, 5.0                             |
| Axial depth of cut (mm) | 1.0, 2.0, 5.0                             |

NC program-less machining that has feedback mechanism for dynamic operation planning can be realized by the developed digital copy milling system with the machining strategy proposed here.
2.3. Experimental verification

The ability or effectiveness of the realized dynamic operation planning is verified in real machining. The digital copy milling system with the machining strategy is executed on a PC/AT computer which is equipped with a Pentium III Xeon 550 MHz CPU, 256MB RAM and Windows NT OS.

The initial cutting parameters (minimum, recommended and maximum values from the left) and the adapted cutting parameters (minimum and maximum values from the left) during the experiment are summarized in Table 1.

The workpiece material is cast iron (FC250), which has $60 \times 60 \times 20$ mm$^3$ in dimensions, and the tool is a carbide ball end mill, which has two flutes and 10.0 mm diameter. Fig. 7 shows the product model ($60 \times 60 \times 15$ mm$^3$) and the tool path pattern for this experiment is the scanning-line mode (zigzag paths). ‘Desired Load’ and ‘Critical Load’ are set 800 and 2000 Nmm in this experiment, respectively.

The records of feed rate, radial depth of cut and spindle torque during machining of the first ‘Face’ are shown in Fig. 8. In this experiment, since the cutting torque of the initial cutting parameters is much smaller than ‘Desired Load’, feed rate is adapted to increase the cutting torque at the beginning of machining.

After the feed rate reaches the maximum value, the greatest load in the ‘Lane’ is still under the limits of the ‘Desired Load’, the radial depth of cut is adapted (from 2.0 to 2.8 mm) and the feed rate is revised to the recommended value (400 mm/min) at the point shown by A in Fig. 8.

Then, though the radial depth of cut is adapted twice at the point shown by B (3.0 mm) and C (3.2 mm), the cutting torque maintains in the range of the ‘Desired Load’. This result shows that cutting parameters are adapted so that machining efficiency becomes better within the range of the ‘Desired Load’.

Fig. 8. Records of cutting parameters and cutting torque.

Fig. 9. Dynamic product planning realized in this study.
The experimental milling of sculptured surface shows the ability or effectiveness of both the digital copy milling system and the proposed machining strategy to adapt cutting parameters during a machining operation. As the result, it is shown that dynamic operation planning for autonomous machining, which does not need any NC program, is realizable.

3. Automatic product planning

It is indispensable to realize not only dynamic operation planning but also dynamic process planning for achieving autonomous machining. And, in order to realize dynamic product planning, product planning should be automated because it takes extensive amount of time and efforts.

(a) Extraction of total removal volume

(b) An example of the division of TRV

(c) Flowchart of the recognition of machining features

Fig. 10. Automatic process planning.
Automatic product planning should have several functions such as the extraction of removal volume, the selection of tools, the decision of cutting parameters and so on. In this study, the flexible planning system which has those functions and can reschedule rapidly during a machining operation is developed by customizing commercial CAD software (using SolidWorks 2003 API). Fig. 9 shows the overview of the developed flexible planning system and the relationship to NC program-less machining realized in this study.

| Feature type   | Determination of tool and its property                                                                 | Tool path pattern   |
|----------------|-------------------------------------------------------------------------------------------------------|---------------------|
| Closed Pocket  | $l < w$ and Tool diameter is $x$. End mill which has maximum diameter to satisfy $x \times 3 \leq l$   | Contour-line mode   |
| Open Pocket    | End mill which has maximum diameter                                                                  | Scanning-line mode  |
| Closed Slot    | $w$                                                                                                  | Scanning-line mode  |
| Open Slot      | $w$                                                                                                  | Scanning-line mode  |
| Face           | Face mill which has maximum diameter                                                                  | Scanning-line mode  |
| Step           | Face mill which has maximum diameter                                                                  | Scanning-line mode  |
| Through Hole   | Drill which fits to hole                                                                              | Drilling mode       |
| Blind Hole     | Drill which fits to hole                                                                              |                     |
| Free Form      | Ball End mill which has maximum diameter                                                              |                     |

Table 2

Automatic operation planning

![Table 2](image_url)

(a) Obtaines TRV and available cutting tools

![Image](image_url)

(b) Comparison of the productivity on different division patterns of TRV

![Image](image_url)

Fig. 11. An example of product planning in the flexible planning system.
By using this system, a real machining operation is executed efficiently considering characteristics of a machine tool and prepared tools as well as geometric features of a product model. Also, for realizing dynamic process planning, it is possible to restart the machining operation following a rescheduling, in case of a sudden cutting trouble like tool breakage.

First, the flexible planning system extracts the total removal volume as the result of the Boolean operation between a workpiece model and a product model as shown in Fig. 10(a). The obtained total removal volume is divided into machining primitives as cuboids and cylinders based on its faces looking to a certain direction (e.g. parallel to XY, YZ or ZX plane) as shown in Fig. 10(b). The operation order is determined by the position, volume and open face of the machining primitives; where open face means the face contacting the air. Machining features, which can select the appropriate tool and tool path pattern for real machining, are recognized from the numbers and positions of the open face of those machining primitives. The flow chart of this proposed machining feature recognition is shown in Fig. 10(c).

Then, resource DB is used to determine the cutting tool, tool property and tool path pattern as shown in Table 2, and also case DB is used to decide cutting parameters. Consequently, some collections of machining features depending on the direction of the division of the total removal volume are obtained to compare their productivity considering a machine tool operated, available tools and so on. Finally, the most suitable collection is selected to start the machining operation automatically. For example, in case of machining primitives and cutting tools shown in Fig. 11(a), the numbers of tool change and assumed cutting time is estimated by information of machining features as shown in Fig. 11(b). And the division pattern 3 (parallel to XY plane) is selected automatically because the cutting time is shortest.

Moreover, in flexible planning system, it is possible to reschedule product planning flexibly and dynamically because the workpiece model is sequentially updated during a machining operation. For this reason, even if tool breakage occurs during a machining operation, the flexible planning system can reschedule and restart the machining operation immediately.

4. Conclusions

In this paper, in order to realize autonomous machining, dynamic product planning is discussed. The results are summarized as follows:

1. The digital copy milling system based on the copy milling principle has been developed. This system can generate tool paths in real time by copying a product CAD model and change cutting parameters during a machining operation.
2. The machining strategy for adapting cutting parameters in real time to maintain stable cutting states has been proposed. NC program-less machining can be achieved by the digital copy milling system with the machining strategy.
3. The flexible planning system has been developed by customizing commercial product CAD software. This system can realize automatic product planning and reschedule them during a machining operation.

As a result, an NC machine tool can be controlled directly, rapidly and autonomously without an NC program for autonomous machining.

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