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Multi-axis machining with additional-axis NC system

S.H. Suh, J.J. Lee, S.K. Kim
Computer Automated Manufacturing Lab
Department of Industrial Engineering
POSTECH, P. 0. Box 125, Pohang, orea, 7@784
Tel: +82-562-279-2196, Fax: +82-562-279-5998
E-mail: shs@gvision.postech.ac.kr, http://camlab.postech.ac.kr

Abstract

While multi-axis machining is an advanced technology for dealing with complex shaped parts with a four or five-axis CNC machine, its application is very limited due to the large amount of investment in practice. The Additional-axis method, typically obtained by attaching rotary/tilt table to the existing three-axis machine, is a powerful alternative to the problem while achieving multi-axis machining. In this research, we attempt to establish a theoretical background and implementation methodology for achieving the genuine multi-axis NC system. The research is composed of : a) the hardware setup for implementing the additional-axis NC system, b) an interface study for implementing multi-axis machining with the hardware configuration, c) versatile CL-data generation algorithms for NC machining, and d) implementation of the algorithms to develop multi-axis CAM system for the additional-axis NC system. Together with a detailed presentation on the above enabling the additional-axis machining system, we will show that the additional-axis system can be effectively used for five-axis machining through two specific application examples.

Keywords

Multi-axis machining, Five-axis machining, Rotary/tilt table application, Additional-axis NC system, CL-data decomposition

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1. INTRODUCTION

With the development of NC technologies, the five-axis machine has been recently introduced to improve the overall efficiency (reducing machining time and enhancing machining accuracy) of machining sculptured surfaces such as automobile bodies, aircraft, and ship hulls [1-2]. Traditional methods for machining sculptured surfaces have been implemented on the three-axis machine with ball-end cutters, requiring long machining time and a hand-finishing process to remove cusps. For more complex surfaces, multiple setup changes (time consuming and a source of inaccuracy). On the other hand there are several aspects limiting the practical application of contemporary five-axis machining technology. First, it requires a large investment to purchase the machine tools (the typical five-axis machining center cost over US$ 1 Million (3). Another limiting factor has been due to the complexity of part programming, requiring supporting software together with programming skills. Thus, for practical propagation of the sophisticated method, an economically feasible method has to be sought. In this paper, we investigate a new method called additional-axis machining technology, utilizing the three-axis CNC machine tools by attaching an additional apparatus, such as an indexing table and a rotary/tilt table (RT table).

2. ADDITIONAL-AXIS NC SYSTEM

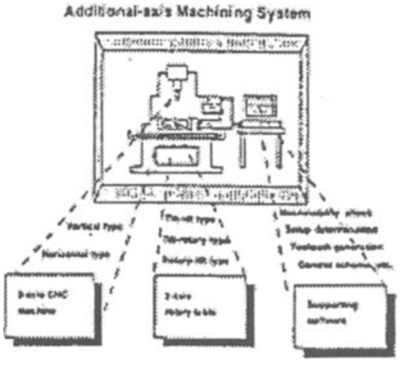

Figure 1. A typical additional-axis machining system.

The additional-axis machining system can be constructed by interfacing manual or servo controlled rotary table to the three-axis machine tools together with supporting software. The typical system shown in Figure 1 is a practical alternative to the problem while achieving five-axis machining. The attachment (manual indexing table or servo controlled rotary/tilt table) has been used practically in the machine shop, as a means for changing part orientation. Note, however, that due to insufficient study on the additional axis machining (specifically on the supporting software), its application has been limited, to simple operations, such as multi-face machining and multiface drilling by the indexing mechanism. In fact, no contemporary CAD/CAM system supports the additional-axis machining methods enabling the five-axis surface machining operations. To extend it for achieving the five-axis machining of free surfaces, various research including: a) hardware interfacing and its control, together with b) supporting software for tool path planning and execution have to be carried out, which has been the theme of our research.

2.1 Configuration code

Five-axis machines, in general, have three linear and two rotational axes. Depending on the arrangement of the five axes, there are a variety of configurations for the 'genuine" five-axis machine (For the details, see [4]).

Theoretically, the additional-axis machine takes a variety of configurations depending on its mechanical structure and controller capability. Table 1 shows various configurations by the following code:

[D_m,C_m, S_m, D_a,S_a]

D_m, : # of axis in the machine,
C_m : # of controllable axis by the machine controller,
S_m : # of simultaneous control axis by the machine controller,
D_a, *:* # of axis in the rotary table,
S_a *:* # of simultaneous control axis for the rotary table.

Table 1. Configurations of the Additional-axis machine

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
* [illegible]	[illegible]	[illegible]
* [illegible]	[illegible]	[illegible]
* [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	* [illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	* [illegible]	[illegible]
[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]
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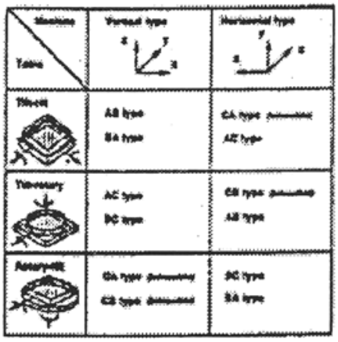


Figure 2. Feasible structure configuration.

Table 1 shows all the configurations for D. = 3. The typical configurations often found in the practice are marked by (*). For example, [3,3,3, 0, 0] means the conventional three-axis machine without an additional-axis, and [3, 3, 3, 2, 0] the three-axis machine tools equipped two-axis manual indexing table. On the other hand, [4,4,3, 1, 1] means the four-axis machine, whose three axes are controlled simultaneously, interfaced with a one-axis servo controlled rotary table. It is worth pointing out that: a) the number of controllable axes should be greater than or equal to the number of simultaneously controlled axes, and b) the number of simultaneous controls is less than or equal to the number of mechanical axes;

$$Cr, \geq S,, , \text{and } D. + D, \geq Sm + S,. \quad (2)$$

In the following Sections, the detailed characteristics for the [3,3,3,2,*] will be discussed for a) structure configuration, b) control scheme of rotary axes, and c) feasible tool orientation.

2.2 Kinematic structure

Based on the structure of the three-axis machine (horizontal and vertical) and the additional two-axis rotary table (tilt/tilt, tilt/rotary, and rotary/tilt), there are 12 types of structure for the additional-axis machine of [3, 3, 3, 2 *] as shown in Figure 2. The AB type means that the A axis is nearer to the machine bed than the B axis. The four structures marked as 'infeasible" do not give two degrees of freedom but one. In this case, the tool does not have five degrees-of-freedom but four. It is interesting to note that these occur when the nearest rotational axis to the machine bed is the C axis. The above analysis shows that the [3, 3, 3, 2, *] should be constructed based on the eight feasible structures.

2.3 Interface scheme of rotary axes

Depending on how the rotary axes are interfaced with the main (three-axis) controller, the control of the rotary axes can be classified into three schemes: a) directly synchronized (DS); where the rotary axes are directly controlled by the main controller, b) indirectly synchronized (IS); where the rotary axes and the machine are controlled independently by two control units, and c) sequential; where the motion of the rotary axes are sequentially executed before or after the machine motion. The genuine DS scheme is only obtained by the originally (not by additionally) five-axis controller. Thus, this scheme can be implemented for the configurations, where Sm, $\geq$ Dm + Da and Sa = 0, marked by ⊕ED in Table 1. In the DS scheme, the main and an additional controller can communicate directly, and hence it is basically the same as the genuine five-axis controller machine tool. Thus, the five-axis CL-data prepared for [5, 5, 5, 0, 0] can be executed by [3, 5, 5, 2, 2]. Note, however, that DS scheme is not common in practice.

In the IS scheme, the rotary axes are controlled by another controller. Thus, the synchronization of the two control units (one for the linear motions and the other for the rotational motions) and the execution method of the CL-data via the two controllers are two issues in the IS scheme. For the configurations (S. < D@ + D,, and S,, $\geq$ 1), (e.g., [3, 3, 3, 2, 1] and [3, 3, 3,2, 21 fail into this group), IS scheme should be employed for five-axis machining. In the sequential scheme, the rotary axes are not controlled simultaneously with the machine. Thus, in order to manufacture the five-axis part with this scheme axis-reduction method" (to be discussed later) should be employed. Sm, = *Cm,* = *Dm, Sm* = 0 fall into this group, and [3, 3, 3, 2, 0] is an example.

2.4 Feasible tool orientation

The feasible tool orientation of the additional-axis machine is determined based on the structure configurations and the number of simultaneous controls for rotary table as well as the rotational limits of rotary axes. Depending on the structure configurations, the feasible tool orientation of the additional axis machine can be classified into three types: a) AC (or BC), b) AB, and c)BA type. Defining the tool orientation as the direction vector on the unit sphere, the feasible tool orientation for the three types can be represented as shown in Figure 3 where AB type is represented by a spherical cone, and AB and BA by spherical rectangles. In the figure, 'great arc" (resp. "Plane arc") represents the rotational motion of the nearest (farthest) rotation4xis he machine bed (i.e., great arc in AC type refers to the rotational motion of the A axis.), and the lengths of these arcs also represent the rotational limit of the rotary axes.

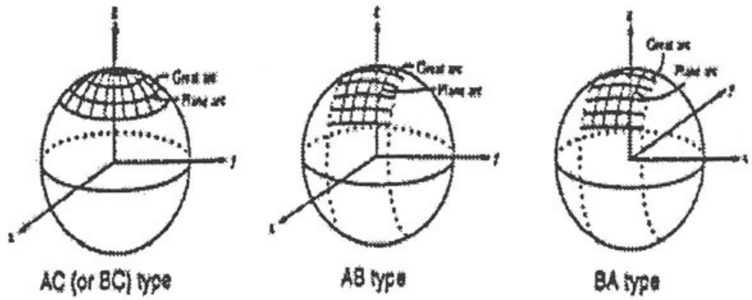


Figure 3. Feasible tool orientations of the three structure types.

Depending on the number of simultaneous controls of the rotary table) the additional-axis machine has three control modes: a) zero control, b) one control, and c) two control. Zero control means that the rotary table is an indexing table. [3,3,3,2, 0], one control means that only one of the two simultaneously controlled (e.g. [3, 3, 3, 2, 1]), and two control axes can be simultaneously controlled (e.g. [3, 3, 3, 2, 2]).

3 VERSATILE CAM (V-CAM) SYSTEM

The key to achieve multi-axis machining with the additional-axis system is the software algorithm for tool path planning and execution for the two systems machine tools and additional axes. Depending on the configuration of the additional-axis system, the issues to be addressed are varied. It should be pointed that the previous tool path planning algorithms for multi-axis NC machining (e.g., Reference [5-71]) cannot be applied to the additional-axis machining environment

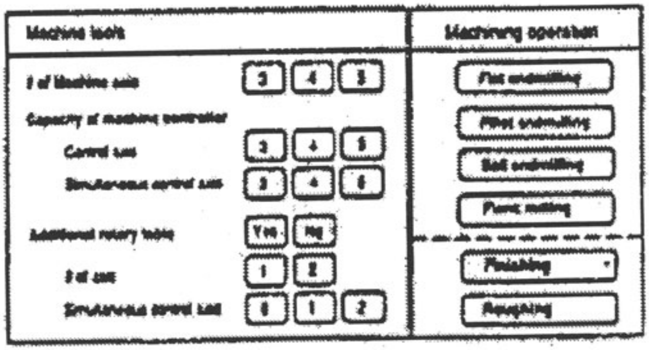


Figure 4. CAM function supported by VCAM.

as the previous methods are valid under the following assumptions: 1) All the axes are simultaneously controlled, 2) The dimension of CL-data is equal to the number of simultaneous controlled axes, and 3) The CL-data is executed by a single controller.

Taking into consideration of type of machining operations (e.g., rough/finish cut, tool shape) together with the hardware configuration, there are various combinations. Figure 4 shows the combination where a finish cut using a ball endmill cutter on a three-axis machine tool with a two-axis manual indexing

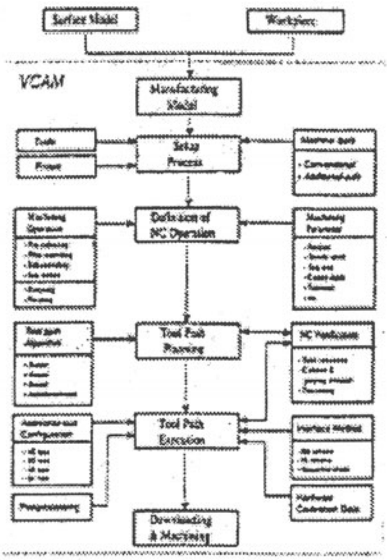


Figure 5. The schematic diagram of VCAM.

a comprehensive CAM system (called Versatile CAM System or V-CAM System). Figure 5 shows the architecture of the V-CAM system capable of generating the tool paths and execution data from the surface model of the part surface. Note that V-CAM system is able to perform conventional CAM functions for multi-axis machining. In particular, the V-CAM system is distinguished from the contemporary CAM system by the shaded and dotted boxes in Figure 5. In the following sections, we briefly describe the details of the algorithms and hardware interfaces implemented on the V-CAM system for two examples; 1) Finish cut ball endmilling with [3, 3,3,2,0], and 2) Finish cut flank milling with [3,3, 3,2,2].

(a) an impeller (b) a section between two blades

Figure 7. Test example.

4 ILLUSTRATIVE EXAMPLES AND DEVELOPMENT

4.1 Example 1: Five-axis ball endmilling with three-axis CNC machine tools and manual indexing table

In this section, we present a versatile CAM method by which the five axis machining can be effectively carried out with a three-axis CNC machine together with a rotary-tilt type indexing table, denoted by [3,3,3,2,0] (see the typical configuration shown in Figure 6). In this environment, the tool orientation is obtained by changing the part setup by the manual indexing table. Thus, to machine the five-axis free surface (free surfaces requiring full five-axis control, see Reference [8] for the details) with this configuration, multiple part setups are required. Note that this is 'fewer-axis machining" as where the number of the simultaneously controllable axes is fewer than required (in this case, the number of simultaneously controllable axes is 3, while the required is 5)To minimize this handicap, we have to seek a tool path planning method (called axis-reduction method") such that: a) The number of part setups (this is to minimize the manual setup change time) and b) The switching effect (this is to minimize the possible tool marks or ridges on the surface where multiple tool paths join).

Table 2: Optimal solutions minimizing part setups.

	Tool axis in polar angle		Indexing table angles		Total number of switchings
	Setup 1	Setup 2	Setup 1	Setup 2	
Alternative 1	(-15,90)	(15,90)	(90,-165)	(90, 165)	31
Alternative 2	(-15,90)	(25,90)	(90,-165)	(90, 155)	37

(a) machinable surface area (b) non-machinable area (c) index table orientation

Figure 8. Minimum setup configuration.

For the test, an impeller shape shown in Figure 7(a) was taken. The impeller is made up of eight blades. It is sufficient to show the developed procedure for the surface between the blades (Figure 7(b)) as the results can be rotated and applied to the rest of the blades. Applying the solution procedure (Note that the details were not given in this paper due to page limitations. See reference [9] for the details), the, minimum number of setups be two, with the setup combinations shown in Table 2, where alternative 1 with 31 switchings (fourth column of Table 2) turned out to be the optimal. See Figure 8 for the comparison of the two setups. Finally, Figure 9 shows the actually machined part.

Figure 9. Results of machining experiment.

4.2 Example 2: 5-Axis flank milling with servo con-trolled rotary/tilt table

Since ruled surfaces are represented by a one-parameter family of straight ruling lines (e.g., a conic surface), they are particularly well suited for five-axis machining using flank milling which is one of the crucial features that the five-axis NC machine offers. Compared with bottom-edge based machining, flank milling can increase productivity significantly as well as improve surface finish. Thus, we developed flank milling method for NC machining of ruled surfaces with the additional-axis machine, the three-axis CNC machine interfaced with a two-axis controlled tilt/rotary table, denoted by [3,3,3,2,2].

In this example, we took the system consisting of a vertical three-axis CNC machine, a servo controlled rotary-tilt table, and a host control system coordinating the machine tool and the rotary table controllers. To achieve five-axis flank milling of the ruled surface with this system, algorithms for tool path planning and execution including CL-data composition and the synchronization method were developed. Due to page limitations, however, we do not describe it here (the details can be found in Reference [10], but we show the results of implementation, calibration and cutting experiment.

4.2.1 Implementation

The presented AFA scheme was implement for Bridgeport 3-axis CNC milling machine run on the three-axis controller (Heidinhain TNC 151 model). A rotary/tilt table (manufactured by Troyke Manufacturing Co.) was interfaced with a two-axis controller (DSP board). The two controllers were coordinated via a host controller, a rotary/tilt table and a host computer where a DSP board is installed together with the V-CAM system.

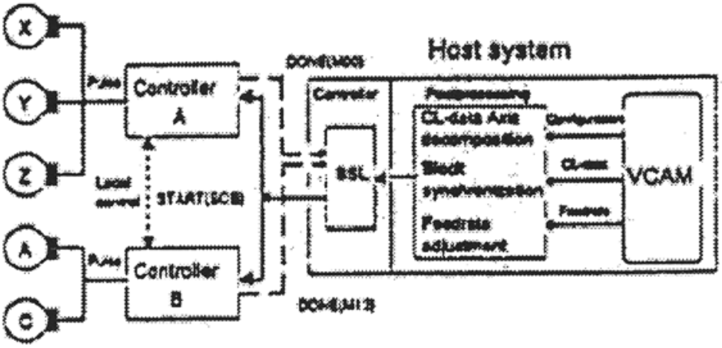
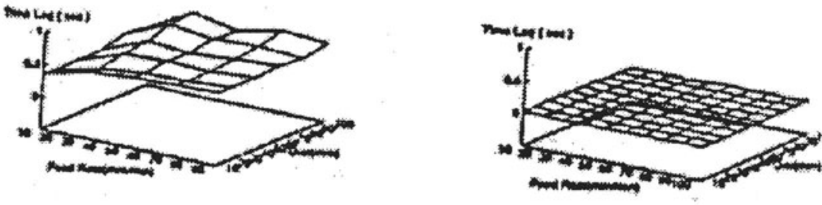


Figure 10. IS control scheme of AFA.

4.2.2 Calibration of the controllers

The practical validity of the above synchronization method is determined based on the difference of the execution time. Without calibration, there exists a time difference in almost all the cases, even if the computed execution time was the same. This is due to the difference in the control logic of the two controllers. Also, it was found that the time difference is dependent on the values of the feed rate and moving distance as shown in Figure 11 9a) (called characteristic map or CM), showing the time difference under various feed rates and distances.

Applying the hardware calibration method, we obtained the characteristic map shown in Figure 11 (b) indicating the maximum of 30 ms throughout the entire range of the moving distance and fee rate. In practice, 30 ms are allowable for most of the precision. Further, as the time difference is constant over the entire range, its effect can be virtually eliminated by compensating the time lag in the



(a) Before calibration (b) After calibration postprocessing procedure.

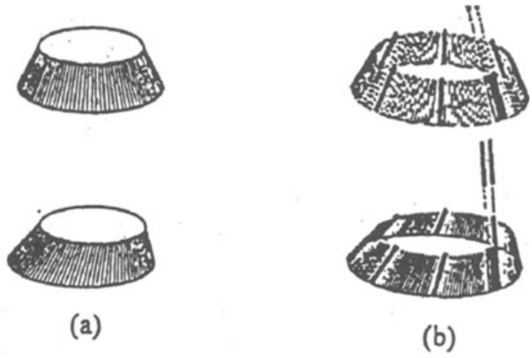


Figure 12. Two cone ruled surfaces

4.2.3 Cutting experiment

Two examples shown in Figure 12 (a) are a ruled surfaces with the circle diameter of 60 mm and 80 mm for the upper and lower base curves. Applying the tool path algorithm, the CL-paths including tool approach and departure were obtained as shown in Figure 12 (b). Applying the procedures of tool path planning followed by path execution, the two parts of G-codes were obtained. By executing the G-codes for the two controllers, parts shown in Figure 13 (c) was obtained. Note that Figure 12 includes the results of rough cut (a) and semifinish cut (b). The finished part showed dimensional accuracy and good surface finish.

(a) rough cut (b) semifinish cut (c) final shape

Figure 13. Cone cutting experiment.

5 CONCLUDING REMARKS

In this paper, the additional-axis machining method was presented with the enabling theories and hardware implementation methods for achieving five-axis machining with three-axis machine tools and an additional attachment. Investegating the characteristic of the additional-axis system, we established the architecture of a comprehensive software (called V-CAM) system, supporting various configurations and machining operations.

To show its validity and provide a detailed illustration, we took two application, we took two application examples: [3,3,3,2,0] and [3,3,3,2,2]. In the first example, using the manual indexing table, the tool orientation is obtained by changing the part setup manually. Since this method is very simple and economical (the indexing table cost a few thousand dollars), it can be effectively applied in the medium to small industry where capital investment for the five-axis system is a burden. With the continuously controlled motion of the rotary/tilt table [3,3,3,2,2] taken in the second example, the additional-axis system performs like a generic five-axis system. We showed that the flank milling operation requiring simultaneous five-axis controls can be effectively carried out by developing tool path planning and execution algorithms together with hardware implementation and the calibration method.

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