Transformation of CAM Data for 5-Axis CNC Machine Spinner U5-620

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***Abstract*— Transformation of a tool path data computed by a commercial Computer -Aided Manufacturing system (CAM) to create a NC program for a 5-axis CNC machine plays an important role in CAM/CNC integration in the mechanical manufacturing industry. This paper presents a kinematic modelling and an inverse kinematic analysis for a 5-axis CNC machine Spinner U5-620. Since the 5-axis machine is comprised of two kinematic chains, which is similar to two cooperative robots, one robot caries the tool and one robot caries the workpiece, the kinematics model of the machine is formulated by unifying the two separate kinematics sub-models of the two kinematic chains. It has shown that the closed form inverse kinematic equation yielded in this study is useful for developing a postprocessor to produce NC programs for the 5-axis CNC machine. By using the developed postprocessor, complex parts composed of sculptured surfaces can be machined effectively with the machine. The real cut part experiments implemented on the machine Spinner U5-620 show the effectiveness of the proposed method.**

***Index Terms*—CAD/CAM, CAM/CAM – CNC integration, Five-axis CNC, Inverse Kinematics, Postprocessor**

I. Introduction

Nowadays, there have been several types of CNC (Computer Numerical Control) machines available in industries: 3-axis CNC machines, 4-axis CNC machines, 5-axis machines, etc. The number of the axes of a CNC machine implies the number of DoFs of the machine's mechanism. It is also the number of the axes which can be simultaneously controlled by the controller of the machine. If the number of the axes of a CNC machine increases, the machining capability, the machining efficiency and the machining effectiveness will increase; however, it requires more complex techniques in programming process. Five-axis milling CNC machine (so-called 5-axis milling Robot [1]) has been known as the most modern and efficient machine tool that can be used for fabricating complex products with complex geometry. The products machined by 5-axis CNC machines have been widely used in several industries such as the mold and die making industry, the aerospace industry, the automotive industry, the shipbuilding industry, etc. Using 5-axis CNC machines integrated with commercial CAM (Computer – Aided Manufacturing) systems, end to-end component design and manufacturing is highly automated.

To create programs for 5-axis CNC machines automatically, commercial CAMs are usually used as an efficient tool, in recent years. However, for 5-axis machining of complex surfaces, CAMs do not give directly the final G-codes files (NC programs). The main function of any commercial CAM systems is to generate the cutter trajectory (tool path), basing the input on the part surface modeling, the surface quality requirement (surface error), the cutter definition, the tool path pattern, etc [2]. This main output of CAMs is the so-call CL data set $\{x_i, y_i, z_i, i_i, j_i, k_i\}$ where $\{x_i, y_i, z_i\}$ are the coordinates of the tool tip, and $\{i_i, j_i, k_i\}$ the directional cosines of the tool axis orientation correspondingly. According to a specific CNC controller, a specific CL data computed by CAMs must be post-processed to compile a NC program for controlling the CNC machine. Notice that although the advanced controllers can accept the CL data to machine the workpiece in real time without the need of postprocessor [3], they are relatively expensive and not commonly used in most industries. Therefore, for any specific 5-axis CNC machine, a corresponding post-processor is usually needed to process CL data computed by CAMs for off-line NC program generation. In traditional CNC machining techniques (2-axis, 3-axis), the orientation of

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the tool axis does not vary in workpiece coordinate system during machining. The CL data can be transferred into G-codes file very easily since only $\{x_i, y_i, z_i\}$ is considered and linear transformation is needed. This transformation regards with the setting of the workpiece zero point and the machining zero point. If the two zero points coincide, the transformation will be neglected. In the case of 5-axis machining, the tool axis orientation can be changed during the machining process, so the directional cosines $\{i_i, j_i, k_i\}$ of the tool axis vector for every tool posture (in each record of the CL data) must be considered.

In general, a post-processor of a 5-axis CNC machine is related to the inverse kinematics of the 5-axis CNC machines [4-8], the linearization of the tool path [1,4], the singularity analysis of the machines [4,9,10], the adjustment of the feed rate [11], the process planning [12], etc. Among the main tasks of a postprocessor, the kinematic modelling and the inverse kinematic analysis is a key point that has gained an increasing attention of many researchers in recent years. This is because commercial 5-axis CNC machines have been designed in a large variety of configurations and structures. In essence, the main goal of the postprocessor development is to transform the CL data $\{x_i, y_i, z_i, i_i, j_i, k_i\}$ into the set of 5-axis displacements as (X, Y, Z, A, B) or (X, Y, Z, A, C) or (X, Y, Z, B, C). X, Y and Z denote the linear axes of a machine, meanwhile (A,B) or (B,C) or (A,C) represent the two rotary axes of an individual machine.

In the literature, some research works have been done for post-processor development for the 5-axis CNC machine DMU 50e [4], a 5-axis CNC machines with non-orthogonal head tilting or nutating configuration [6,7], a 5-axis CNC machines with non-orthogonal rotary axes [8]. Thought some post-processors are available such as the ones in [4-8], they cannot be applied for other 5-axis CNC machines such as the machine Spinner U5-620. Therefore, in this paper, a kinematic modeling and a post-processor construction for the machine Spinner U5-620 are presented. The proposed post-processor is implemented and validated by using numerical simulation scenarios and real cut parts. It is shown that the post-processor is useful and applicable for producing NC programs for the machine Spinner U5-620, and thus the use of the post-processor is effective and efficient for machining complex parts with the machine.

II. Kinematic Modelling and Inverse Kinematics for Spinner U5-620

Let's consider the configuration of the 5-axis CNC machine Spinner U5-620 in Fig. 1. The five axes of the machine are denoted as X, Y, Z, B and C as shown in Fig. 2.

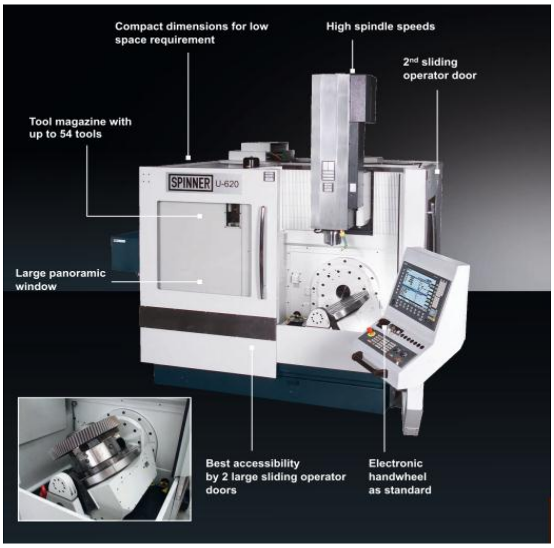


Figure 1. Spinner U5-620.

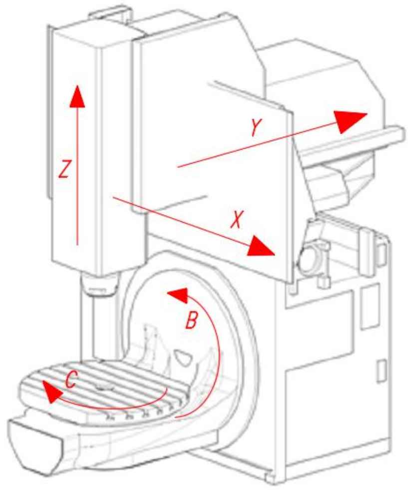


Figure 2. The configuration of Spinner U5-620

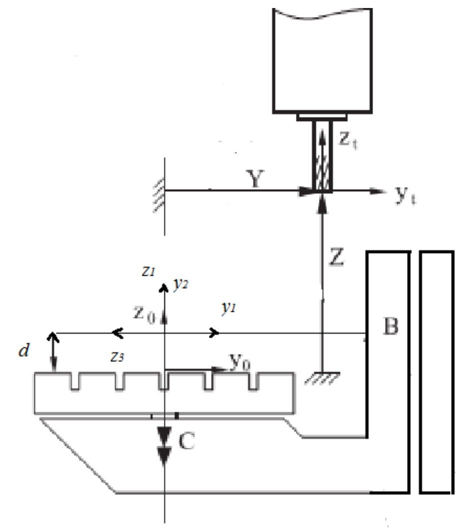


Figure 3. Coordinate systems for Spinner U5-620

As shown in Fig. 3, seven Castersian coordinate systems are defined as follows.

$x_0y_0z_0$ is the base coordinate system, located in the center of the table surface when $B = C = 0^0$.

$x_1y_1z_1$ is a translation of $x_0y_0z_0$ at a distance d along z_0.

$$\mathbf{T}_0^1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$x_2y_2z_2$ is a rotation of $x_1y_1z_1$ at an angle $\pi/2$ around x_1.

Frame $x_0y_0z_0$, frame $x_1y_1z_1$ and frame $x_2y_2z_2$ are fixed; they do not move with the machine axes.

$$\mathbf{T}_1^2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$x_3y_3z_3$ is a rotation of $x_2y_2z_2$ at an angle B around z_2.

$$\mathbf{T}_2^3 = \begin{bmatrix} \cos B & -\sin B & 0 & 0 \\ \sin B & \cos B & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$x_4y_4z_4$ is a rotation of $x_3y_3z_3$ at an angle $-\pi/2$ around x_3.

$$\mathbf{T}_3^4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$x_5y_5z_5$ is a translation of $x_4y_4z_4$ at a distance d along z_4. The frame $x_5y_5z_5$ is always located at the center of the machine table, also after the B axis has been rotated.

$$\mathbf{T}_4^5 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$x_wy_wz_w$ is the workpiece coordinate system which is obtained by rotating $x_5y_5z_5$ at an angle C around z_5.

$$\mathbf{T}_5^w = \begin{bmatrix} \cos C & \sin C & 0 & 0 \\ -\sin C & \cos C & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Note that $x_0y_0z_0$ is the reference frame located in the workspace of the machine, and it does not depend on the motion of the machine axes. $x_3y_3z_3$ is the frame fixed the body connecting with the machine frame by the revolution joint B.

$x_ty_tz_t$ is a frame fixed to the milling tool with the origin at the tool tip.

$$\mathbf{T}_0^t = \begin{bmatrix} 1 & 0 & 0 & X \\ 0 & 1 & 0 & Y \\ 0 & 0 & 1 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

The tool position and orientation represented in the workpiece coordinate system $x_wy_wz_w$ can be obtained as

$$\mathbf{T}_w^t = \mathbf{T}_w^5\mathbf{T}_5^4\mathbf{T}_4^3\mathbf{T}_3^2\mathbf{T}_2^1\mathbf{T}_1^0\mathbf{T}_0^t \tag{8}$$

where $\mathbf{T}_w^t$ is a function of the machine axis variables X, Y, Z, B and C.

Equation (8) can be transformed in the following form.

$$\mathbf{T}_w^t = \left(\mathbf{T}_5^w\right)^{-1}\left(\mathbf{T}_4^5\right)^{-1}\left(\mathbf{T}_3^4\right)^{-1}\left(\mathbf{T}_2^3\right)^{-1}\left(\mathbf{T}_1^2\right)^{-1}\left(\mathbf{T}_0^1\right)^{-1}\mathbf{T}_0^t \tag{9}$$

The matrix $\mathbf{T}_w^t$ is yielded as

$$\mathbf{T}_w^t = \begin{bmatrix} \cos B\cos C & -\sin C & \sin B\cos C & X\cos B\cos C - Y\sin C + Z\sin B\cos C - d\sin B\cos C \\ \cos B\sin C & \cos C & \sin B\sin C & X\cos B\sin C + Y\cos C + Z\sin B\cos C - d\sin B\sin C \\ -\sin B & 0 & \cos B & -X\sin B + Z\cos B - d\cos B + d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix $\mathbf{T}_w^t$ describes the tool axis orientation and the tool tip position of the tool in the workpiece coordinate system $x_wy_wz_w$. Notice that the three entries of the third column of the matrix $\mathbf{T}_w^t$ are the three cosines of the tool vector as

$$i = \sin B\cos C \tag{10}$$

$$j = \sin B\sin C \tag{11}$$

$$k = \cos B \tag{12}$$

The three entries of the last column represent the tool tip position as

$$x = X\cos B\cos C - Y\sin C + Z\sin B\cos C - d\sin B\cos C \tag{13}$$

$$y = X\cos B\sin C + Y\cos C + Z\sin B\cos C - d\sin B\sin C \tag{14}$$

$$z = -X\sin B + Z\cos B - d\cos B + d \tag{15}$$

The equations (10-15) are the forward kinematic equations of the machine.

The inverse kinematic equations can be obtained by using the following expression.

$$\mathbf{T}_t^w = \left(\mathbf{T}_w^t\right)^{-1} = \left(\mathbf{T}_w^5\mathbf{T}_5^4\mathbf{T}_4^3\mathbf{T}_3^2\mathbf{T}_2^1\mathbf{T}_1^0\mathbf{T}_0^t\right)^{-1} \tag{16}$$

Therefore,

$$\mathbf{T}_t^w = \left(\mathbf{T}_0^t\right)^{-1}\mathbf{T}_0^1\mathbf{T}_1^2\mathbf{T}_2^3\mathbf{T}_3^4\mathbf{T}_4^5\mathbf{T}_5^w \tag{17}$$

Finally, the following inverse kinematic equations can be yielded as

$$X = x\cos B\cos C + y\cos B\sin C - z\sin B + d\sin B \tag{18}$$

$$Y = x\sin C + y\cos C \tag{19}$$

$$Z = x\sin B\cos C + y\sin B\sin C + z\cos B - d\cos B + d \tag{20}$$

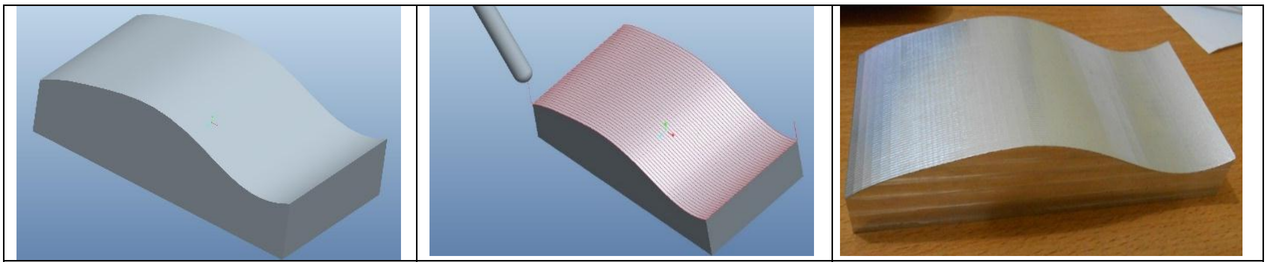
$$B = \arccos\left(k\right) \tag{21}$$

$$C = \arctan 2\left(\frac{j}{\sin B}, \frac{i}{\sin B}\right) \tag{22}$$

III. Postprocessor Implementation and Experiments

The main algorithm of the postprocessor program can be described as follow.

Loop the following steps for all the CL points in a CL data computed by CAMs.



a) Designed part | b) Tool path | c) Real cut part

Figure 4. Tool path planning and real cut part

- Step 1: reading the current CL point $\left(x_i, y_i, z_i, i_i, j_i, k_i\right)$.

- Step 2: calculating $\left(X_i, Y_i, Z_i, B_i, C_i\right)$ by using equations (18-22).

- Step 3: writing a G-code syntax accordingly.

The algorithm is implemented in Visual Studio environment and it is tested with several examples for the G-codes generations, based on CL data files computed by a CAM software (ProE 4.0).

In order to demonstrate the postprocessing algorithm, one freeform surface is designed in CAD and machined with the machine spinner U5-620. The designed surface is shown in Fig. 4a, the tool path calculated is shown in Fig. 4b, and the real cut part is presented in Fig. 4c.

The CL data is as follows.

```
$$*        Pro/CLfile  Version 4.0 - M030
$$-> MFGNO / MFG0001
PARTNO / MFG0001
$$-> FEATNO / 36
MACHIN / UNCX01, 1
$$->          CUTCOM_GEOMETRY_TYPE          /
OUTPUT_ON_CENTER
UNITS / MM
LOADTL / 1
$$-> CUTTER / 12.000000
$$->    CSYS    /    1.0000000000,    0.0000000000,
0.0000000000, 0.0000000000,  $
        0.0000000000,  1.0000000000,  0.0000000000,
0.0000000000,  $
        0.0000000000,  0.0000000000,  1.0000000000,
0.0000000000
SPINDL / RPM, 5000.000000,  CLW
RAPID
GOTO     /     -6.0000000000,     -6.0000000000,
10.0000000000
FEDRAT / 50.000000,  MMPM
GOTO    /    -6.0000000000,    -6.0000000000,    -
5.0000000000
GOTO   /   -194.0000003412,   -6.0000000000,   -
5.0000000000
…
```

After postprocessing, the G-codes obtained are as follows.

```
G21
T3 M6
M8
S3000
G0 X-92.006 Y-50.000 Z72.439 B25.607 C0.000
G0 X-67.633 Y-50.000 Z21.585 B25.607 C0.000
F500
G1 X-67.633 Y-50.000 Z17.585 B25.607 C0.000
G1 X-67.602 Y-50.000 Z17.596 B25.598 C0.000
…
```

The demonstrated experiment validated well the kinematic modelling and the postprocessing algorithm presented in this study.

IV. Conclusion

In this study, a real problem of integrating CAM data into a 5-axis CNC machine Spinner U5-620 was solved. A postprocessor algorithm to transform common CL data files for the machine was constructed, which is based on the inverse kinematic modelling of the machine. The postprocessor program was successfully tested and validated through real cut experiments. It was shown that the postprocessor program built in this study is useful and applicable for producing freeform surface NC programs for the 5-axis CNC machine Spinner U5-620. Further, this algorithm could be extended for other 5-axis CNC machines of the same kinematic configuration. Optimization of the feed rate for a large workpiece machining is the future work of this study.

Conflict of Interest

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Chu A My proposed the idea and stated the problem for the research. He checked with the kinematic modelling of the 5-axis CNC machine, and wrote the paper. Nguyen V Cong conducted the kinematic modelling and analysis of the 5-axis CNC machine. Nguyen Minh Hong implemented the experiments on the machine Spinner U5-620. Erik L J Bohez revised all the contents of the paper, and gave several valuable comments to improve the quality of the paper. All authors had approved the final version.

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