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DEVELOPMENT OF A POSTPROCESSOR FOR MILLING WITH A ROTARY AXIS AND VERIFICATION ASSISTED BY VIRTUAL MACHINING ENVIRONMENT

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Abstract: *This paper presents the development of a postprocessor for a vertical milling machine with one rotary axis, commonly known as mill-turn. The subject of this analysis is the 4-axis machine MultiProDesk, whose kinematic structure formula is A'Y'OXZ. A postprocessor is a software that transforms the CL file into a machine-readable G-code. The CL file contains the universally formulated toolpath in sets of tool positions and orientations regarding the workpiece coordinate system. The inverse kinematic model method was used to derive the equations needed to transform the CL data into the displacement of the machine's axis. The displacements of the machine's axis are then implemented into a series of commands in the G-code. Machine kinematics can be designed as two unified kinematic chains with the same origin. The inverse kinematic equations were implemented in a postprocessing algorithm in the Matlab software. In order to test the derived equations, a virtual machining environment was developed. The proposed kinematic model was tested using several test workpieces with different machining strategies. The virtual simulation resulted in a virtual workpiece that matched the original workpiece used to calculate the toolpath, verifying the machine's developed postprocessor.*

Keywords: *post-processor, inverse kinematics, verification, simulation, virtual machine tools*

1. INTRODUCTION

Adding a rotary axis to a conventional three-axis milling machine greatly increases the complexity of the potential parts manufactured on said machine. Machines with one rotary axis on the machine table are commonly known as mill-turn machines, as they combine both milling (*tool rotating*) and turning (*workpiece rotating*) motions. These machines are classified as multi-axis machines, given that the manufacturing process can be obtained by simultaneously utilising all four of the machine's axes. In conventional three-axis milling, the tool orientation does not change during machining. In four- and five-axis machines, the additional rotary axes enable the control of the tools' orientation during the machining process. The alternating orientation of the tool requires a more complex approach to programming multi-axis machines. With complex parts requiring programs with many lines and the utilisation of the tools axis, multi-axis machines are almost exclusively programmed using CAM systems. CAM software include postprocessors developed for a specific machine regarding its kinematic structure. A postprocessor is a software used to generate G-code for a specific machine by transforming the data in a general machining program. Typically, when developing a machining program, first, the toolpath is formed in a general machining program called the CL file, which contains data that describe the position and orientation of the tool regarding the workpiece coordinate system. The CL file is then converted into a G-code using a postprocessor, containing the specific machine kinematics and control functions.

Many approaches to developing kinematic models of machine tools for postprocessing were formed. As the complexity of machines grew, many researchers focused on developing the kinematic models of five-axis machine tools with orthogonal axes. Lee and She focused on developing an inverse kinematic model for three typical types of five-axis machines with orthogonal axes [1]. Based on that work, postprocessing software for specific types of machines were developed in [2-3]. Given the similar approach in the modelling of kinematic structures of five-axis machine tools, there were many attempts to unify the approach into a universal model for postprocessing, such as shown by Chen [4]. With the development of composite machine tools, meaning the machine tools combining milling and turning, there is a need for research for corresponding postprocessors, such as in the work of Tang et al. [5].

This paper focuses on developing a postprocessor for the machine MultiProDesk [6]. The machine is currently a vertical three-axis mill with additional rotary axes in preparation. The kinematic equations implemented into the software are derived using the inverse kinematic method. The software used in this paper is a revised version of the software developed in [7]. In order to verify the postprocessing program and the kinematic equations, a virtual machining simulation was carried out. The three-axis machine model was enhanced with the fourth rotary axis A and used for creating a virtual machining simulation in the Vericut software.

2. INVERSE KINEMATIC TRANSFORMATION OF THE MACHINE

The kinematic equations that describe the machine axis motions regarding the workpiece coordinate system are obtained using the inverse kinematic model. In this method, machine tools are defined as two kinematic chains with the same origin, one carrying the tool and the other carrying the workpiece. On the machine, these kinematic chains represent serially connected translational and rotational joints. Deriving the kinematic equations of the machine starts with assigning each of the moving joints a coordinate system and defining the relative motions between these joints. When defined, these equations will provide a link between the tool position and orientation and the displacements of the axes of the machine. By defining each machine link with a coordinate system, the relative motions of the joints can be defined with elementary transformational matrices. The composition of the elementary transformational matrices yields a complex transformation which can include both translational and rotary transformations. An illustration of the machine's axes and the necessary transformation matrices is shown in Fig. 1.

As outlined above, the kinematic structure of the four-axis machine is defined using two open kinematic chains. The first chain contains

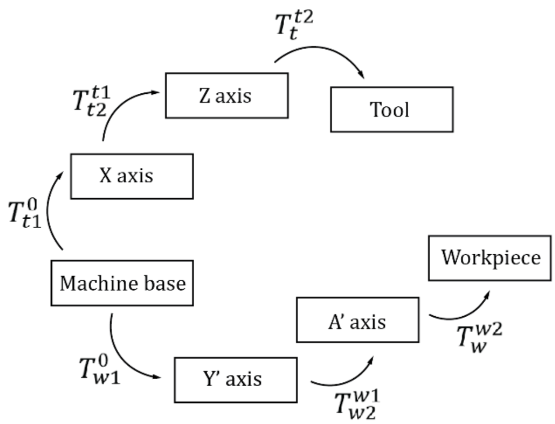

Figure 1. Schematic diagram of machine tool kinematic chains

the joints actuating the motions of the workpiece, called the workpiece coordinate chain. In compliance with the machine tool structure, A'Y'OXZ, the first kinematic chain includes the Y and A axes of the machine. The coordinate systems of the workpiece coordinate chain, $Ox_{w1}y_{w1}z_{w1}$ and $Ox_{w2}y_{w2}z_{w2}$, and the base coordinate system, $Ox_0y_0z_0$, are shown in Fig. 2. The first elementary transformational matrix, T_{w1}^{0} , defines the translational displacement of the machine's Y axis.

$$T_{w1}^{0} = \begin{bmatrix} 1 & 0 & 0 & x_{w1} \\ 0 & 1 & 0 & Y - y_{w1} \\ 0 & 0 & 1 & z_{w1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The adjacent machine axis is the rotary axis A. The elementary transformational matrix defines the relative displacements of the rotary axis to the Y-axis coordinate system.

$$T_{w2}^{w1} = \begin{bmatrix} 1 & 0 & 0 & x_{w2} \\ 0 & cos(A) & -sin(A) & 0 \\ 0 & sin(A) & cos(A) & z_{w2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

In the previous matrices, values $x_{w1}, y_{w1}, z_{w1}, x_{w2}$ and z_{w2} are constant and represent the distances along the X and Z axes between the joint coordinate systems. The only variable values are Y and A, representing the necessary displacements of the machine's translation axis and the necessary rotation angle of the machine's rotary axis.

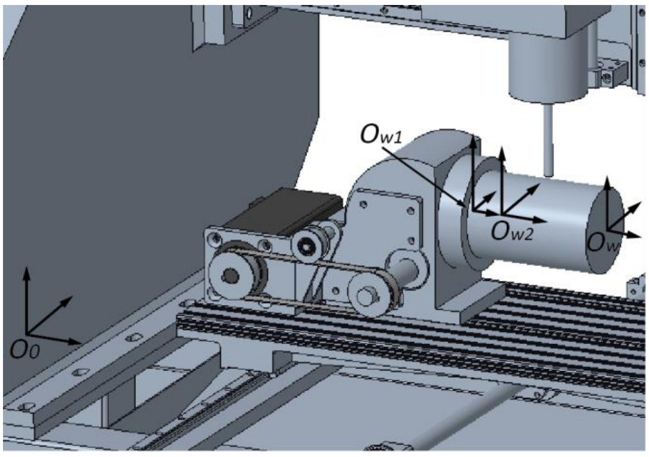

Figure 2. The position of the coordinate systems of the workpiece kinematic chain

A transformational matrix defining the workpiece coordinate system's position completes the workpiece kinematic chain, as shown below. This matrix does not have any variables, as the workpiece is fixed.

$$T_{w}^{w2} = \begin{bmatrix} 1 & 0 & 0 & x_{w} \\ 0 & 1 & 0 & y_{w} \\ 0 & 0 & 1 & z_{w} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The second kinematic chain, or tool kinematic chain, defines the machine's X and Z axis displacements. The coordinate systems of the tool coordinate chain, $Ox_{t1}y_{t1}z_{t1}$ and $Ox_{t2}y_{t2}z_{t2}$, and $Ox_ty_tz_t$, are shown in Fig. 3. Defining the tool kinematic chain equations begins with the transformation matrix between the machine's X axis and the base coordinate system.

$$T_{t1}^{0} = \begin{bmatrix} 1 & 0 & 0 & X - x_{t1} \\ 0 & 1 & 0 & y_{t1} \\ 0 & 0 & 1 & z_{t1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The relative displacement of the X and Z axis are defined with the following matrix:

$$T_{t2}^{t1} = \begin{bmatrix} 1 & 0 & 0 & x_{t2} \\ 0 & 1 & 0 & y_{t2} \\ 0 & 0 & 1 & Z - z_{t1} - H_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

The last coordinate system, located at the tool tip, is defined to complete the tool

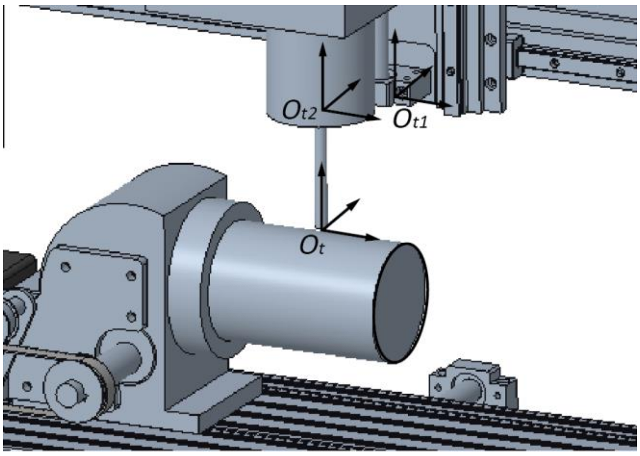

Figure 3. The position of the coordinate systems of the tool kinematic chain

kinematic chain. The transformation matrix that defines this coordinate system contains the tool length correction.

$$T_t^{t2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & H_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

As defined above, the CL file contains information about the position and orientation of the tool in points along the toolpath. The position and orientation of the tool regarding the workpiece coordinate system can also be defined using a transformation matrix - T_t^w. The T_t^w matrix can be derived as a function of the machine's axis displacements using the above elementary transformation matrices.

First, the tooltip vector regarding the base coordinate system can be described in two ways, either using the workpiece kinematic chain or the tool kinematic chain, as stated below.

$$r_t^0 = T_{w1}^0 \cdot T_{w2}^{w1} \cdot T_w^{w2} \cdot T_t^w \quad (7)$$

$$r_t^0 = T_{t1}^0 \cdot T_{t2}^{t1} \cdot T_t^{t2} \quad (8)$$

The previous equations are equivalent and can be defined in the form shown in Eq. 9.

$$T_{w1}^0 \cdot T_{w2}^{w1} \cdot T_w^{w2} \cdot T_t^w = T_{t1}^0 \cdot T_{t2}^{t1} \cdot T_t^{t2} \quad (9)$$

Arranging Eq. 9 to get the matrix T_t^w in the form of a function is shown in Eq. 10.

$$T_t^w = (T_w^{w2})^{-1} \cdot (T_{w2}^{w1})^{-1} \cdot (T_{w1}^0)^{-1} \cdot T_{t1}^0 \cdot T_{t2}^{t1} \cdot T_t^{t2} \quad (10)$$

The transformation matrix is the result of the composition of all elementary transformation matrices and, as such, is a function of all of the defined displacements of the machine's axes: X, Y, Z and A. The derived matrix contains information on the position and orientation of the tool regarding the workpiece coordinate system. It can provide the equations needed to calculate the displacements of the machine's axes by equating the matrix element with CL data. The resulting matrix has the following form:

$$T_t^w = \begin{bmatrix} u_x & v_x & w_x & p_x \\ u_y & v_x & w_y & p_y \\ u_z & v_z & w_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

The matrix shown in Eq. 11 represents the transformation between the workpiece and tool coordinate systems. In the third column are the cosines of the tool coordinate system that are used for deriving the equations for the rotary axis angle.

$$w_x = 0 \quad (12)$$

$$\mathrm{w_y} = \sin(A) \quad (13)$$

$$w_z = \cos(A) \quad (14)$$

Solving the above equations results in the necessary angle of the rotary axis. The fourth column of the resulting matrix represents the displacements of the translational axis, with compensation to counteract the movements of the rotational axis.

$$p_x = a_1 \quad (15)$$

$$p_y = b_1 \sin(A)\,(Z + b_2) - b_3 \cos(A)\,(Y + b_4) \quad (16)$$

$$p_z = c_1 \sin(A)(Y + c_2) - c_3 \cos(A)(Z + c_4) \quad (17)$$

In the previous equations, a_i, b_i, and c_i $(i = 1...3)$ are constant values resulting from the constant distances between the coordinate systems. Solving the system Eq. 15-17 results in the final values of the machine axis displacements.

3. POSTPROCESSOR IMPLEMENTATION

In order to test the derived kinematic model, the solutions to Eq. 12-17 were implemented into the postprocessing software developed in [7]. This program is based on an iterative algorithm, where each command in the CL file is read, calculated, and then translated into a separate file using the G-code syntax.

2.1 Rotary axis correction

The equation for the necessary rotary angle of the axis A is given in Eq. 18

$$A = atan2(w_y, w_z) \tag{17}$$

Given the origin of the trigonometric function, the resulting angle has constraints in the form of $A = [-\pi, \pi]$. In order to prevent errors during machining, an addition to the postprocessing software was made. At the beginning of the program for a given machining process, it is determined if the A axis moves clockwise or anticlockwise. As the calculated angles approach the limit, the values are controlled until that limit is surpassed. Suppose the angles surpass the limit during the machining process. In that case, a correction is made so that the tool continues the motion matches the one at the beginning of the machining, clockwise or anticlockwise.

4. KINEMATIC MODEL VERIFICATION

In order to verify the kinematic model of the four-axis machine, MultiProDesk, two test models were created, shown in Fig. 4. The manufacturing process for the test workpieces was created using the PTC Creo software, with the result being the CL file of both manufacturing processes. The CL toolpaths for both test pieces were then translated using the developed postprocessing program. Generated G-code programs were then tested on a virtual model using the Vericut software, where it is possible to simulate a material removal process. For the first experiment, a workpiece with a concave surface was formed to control the machine's axis motion simultaneously. The workpiece, the machining process, and the resulting virtual manufactured part are shown in Fig. 5. A cylinder workpiece with a spiral groove was formed for the second experiment to test the rotary axis correction. The

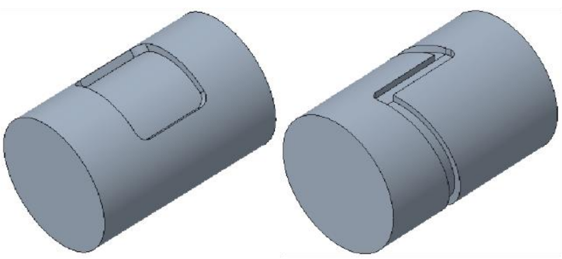

Figure 4. Test workpieces

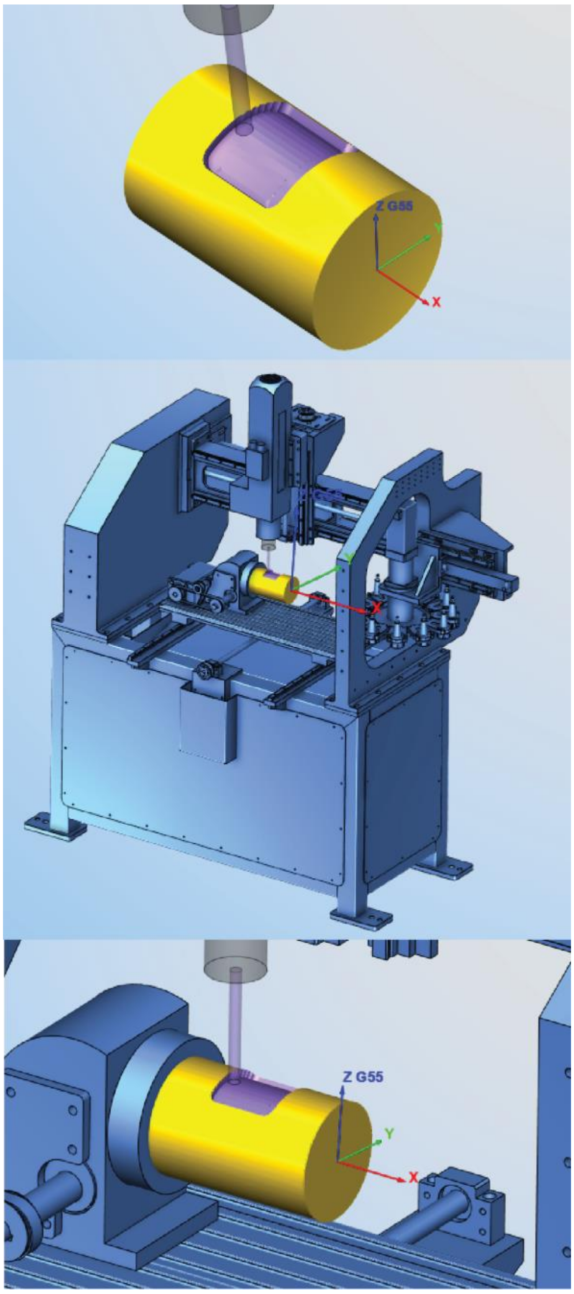

Figure 5. Testing the G-code in Vericut, first test

workpiece, the machining process, and the resulting virtual manufactured part for the second experiment are shown in Fig. 6.

Given that the material removal simulation was conducted using only the G-code program and that the virtual model of the machine corresponds to the real-life machine, both of these experiments can be classified as virtual machining. The virtual machined parts were saved in a standard CAD format and compared to the desired parts, where it was concluded that the experiments were successful.

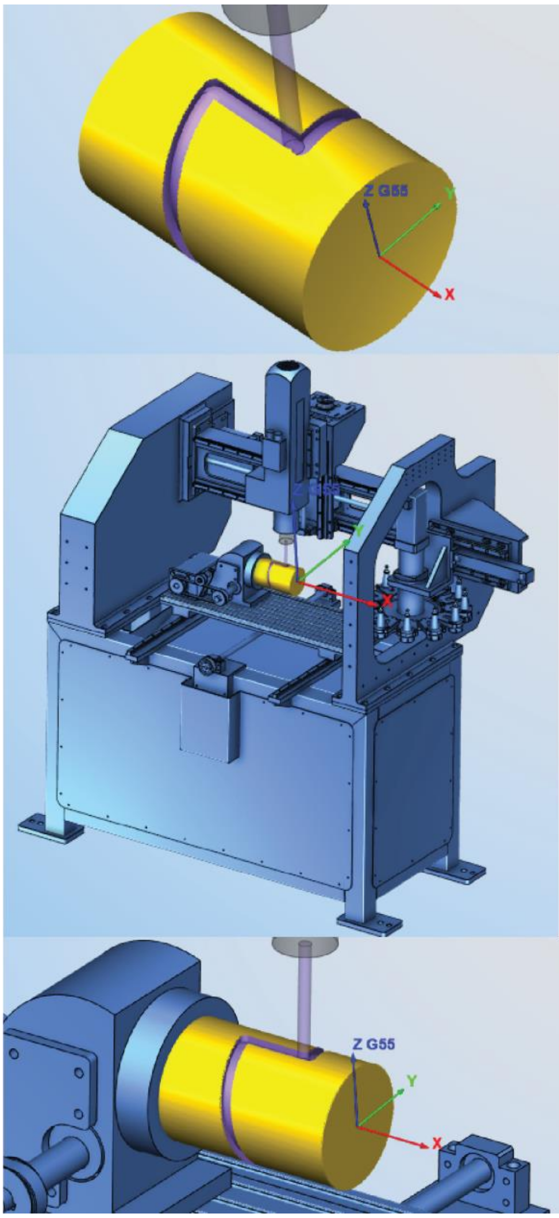

Figure 6. Testing the G-code in Vericut, second test

5. CONCLUSION

A method of developing a postprocessor used for converting a CL file into G-code was presented in this paper. The main objective is the kinematic modelling of a four-axis machine. The kinematic model of the machine was developed using the inverse kinematic method. The kinematic model was implemented into the postprocessing software with an addition of the rotary axis correction.

The results were tested in the form of virtual machining a virtual machine. The method for deriving the necessary equations can be utilised for various types of multi-axis machines, as it provides flexibility for various machine configurations. Further research can be extended by developing postprocessing software for different configurations of the machine's rotary axis.

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