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# Machine models and tool motions for simulating five-axis machining

Stephen Mann [a,*], Sanjeev Bedi [b,1], Gilad Israeli [a], Xiaoran (Linda) Zhou [a]

[a] University of Waterloo, David R. Cheriton School of Computer Science, Waterloo, Ontario, Canada N2L 3G1
[b] University of Waterloo, Department of Mechanical Engineering, Waterloo, Ontario, Canada N2L 3G1

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ABSTRACT

This paper presents a method of determining the tool motion of a five-axis machine. The method is motivated by the imprint point method, where points on the machined surface are computed based on the tool position and tool motion. While simple linear motion can be used as a coarse approximation to this motion, this paper looks at more accurate models of tool motion based on machine kinematics that can be generalized and applied to any CNC machine with one tool head. A kinematic chain is created by decomposing the linear motion of a machine's translational and rotational axes into parameterized affine transformations, and a hierarchical model of the machine combines the transformations to provide an accurate model of machine motion.

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## 1. Introduction

Automation of the manufacturing process from the nominal part geometry on a CAD system to the final machined part offers the opportunity for huge gains in productivity and cost savings. The advent of five-axis machining and methods for generating NC tool paths has already offered the opportunity to reduce machining time by up to 85% [1]. However, this added flexibility also brings added complexity. Research efforts have concentrated on generating interference-free NC tool paths that also produce machined parts free from excessive gouging or under-cutting. Central to these ideas is the generation of the swept volume of the tool along its programmed NC tool path, and the ideas of the simulation, verification and correction of NC tool path programs [2].

Errors can be introduced in the process of going from the design surface to the machined part; in particular, the surface is converted from a smooth mathematical surface into discrete tool positions by CAD/CAM software, and this subdivision into tool positions introduces error [3]. However, to verify that the final toolpath will result in a machined surface that accurately represents the mathematical surface, one does not need to consider the sources of these errors. Instead, one can machine the surface and measure it with a coordinate measuring machine (CMM). Since machining and measuring are expensive processes, one would prefer to *simulate* the machining actions, and measure the error in the computer-generated machined surface. Clearly, this requires that the computer-generated surface be an accurate representation of what would actually be machined.

Thus, for verification, there are three surfaces to be considered. First, there is the surface that one wishes to machine, for which there is usually a mathematical model. Second, there is the surface actually produced by the physical machine, which can be measured with CMMs or other devices. And third, there is the computer-generated simulated surface, which can be used before machining to determine if there is gouging, etc., and to give some confidence in the final result. Some care must be taken in generating the simulated surface, since while it is possible to simulate a tool that moves along perfect mathematical tool paths, what is desired is a simulation that accurately reflects the surface that will be physically machined. Since the machine is limited in the tool motions it can execute, care must be taken to ensure that the simulation matches the mechanics of the actual machine.

To simulate the surface being machined, we need to compute the surface swept by the tool. To compute the swept surface, one must be able to determine curves on the tool whose imprint will be left on the stock as the tool moves. A *grazing point* is a point on the surface of the tool whose direction of motion is perpendicular to the surface normal at that point. For machining, these points are significant, because at any other point on the tool surface, the stock either will have already been machined away or will be machined away in the next instance in time (Fig. 1). For any tool position, the grazing points on the tool are the only ones that might also remain as points on the machined stock.

As one example of where the direction of motion is used when computing a swept surface, consider a moving cylinder of radius $R$. For a point $P$ on the axis of a cylinder, if $P$ has a direction of motion $d$, then we can compute two grazing points on the cylinder by first

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[*] Corresponding author. Tel.: +1 519 888 4567; fax: +1 519 885 1208.
*E-mail addresses:* smann@uwaterloo.ca (S. Mann), sbedi@uwaterloo.ca (S. Bedi), gilad.israeli@gmail.com (G. Israeli), x7zhou@cgl.uwaterloo.ca (X. Zhou).
[1] Tel.: +1 519 888 4567; fax: +1 519 888 6197.

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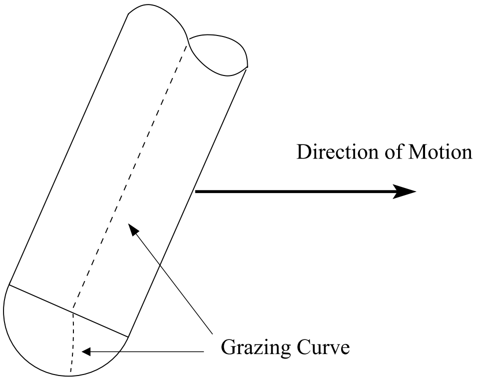

**Fig. 1.** Points on the tool surface on the direction of motion side of the grazing curve are about to be machined away; points on other side of the grazing curve have already been machined away.

computing

$$v = R\frac{d \times a}{|d \times a|}, \quad (1)$$

where $a$ is the direction of the cylinder's axis. Then $P \pm v$ are two grazing points on the cylinder. By varying $P$ along the cylinder's axis, we can compute two grazing curves on the cylinder. For further details on this computation and for its generalization to arbitrary surfaces of revolution, see [4,5].

As a second example where the direction of motion is needed when computing the swept surface, consider the sweep-envelope differential equation (SEDE) method [6]. With the SEDE method, the positions and directions of motions of grazing points are used to compute the path of the swept grazing points. These are then extended to the swept surface. Thus, the SEDE method also needs the direction of motion of points on the tool surface.

In earlier papers [4,5], we gave a method to generate the surface swept by a moving tool in five-axis machining. However, both of those five-axis machining papers assumed a piecewise linear motion of the tool, with rotations occurring around the tool tip. Such an approximation can at times be grossly wrong. For example, consider the two consecutive tool positions shown on the top left in Fig. 2. In the linear approximation method, the two vectors $\vec{t}_i$ and $\vec{t}_{i+1}$ are blended to create intermediate tool positions. The actual motion may be very different for some tool positions on some machines, since the machine parameters are linearly interpolated between the tool positions. For example, on a rotary table machine (Fig. 3, right), the movement from $\vec{t}_i$ to $\vec{t}_{i+1}$ may cause the tool/workpiece to rotate by an angle $\theta$. During this rotation, the tool may go over unplanned areas and may leave deep gouges. The difference in cuts between the two motions is illustrated on the bottom of Fig. 2.

This type of problem (where the machine motion differs greatly from pure linear motion) occurs for example when machining a crest or valley on a curved surface, and is encountered frequently in machining of automotive dies. Essentially, these problems

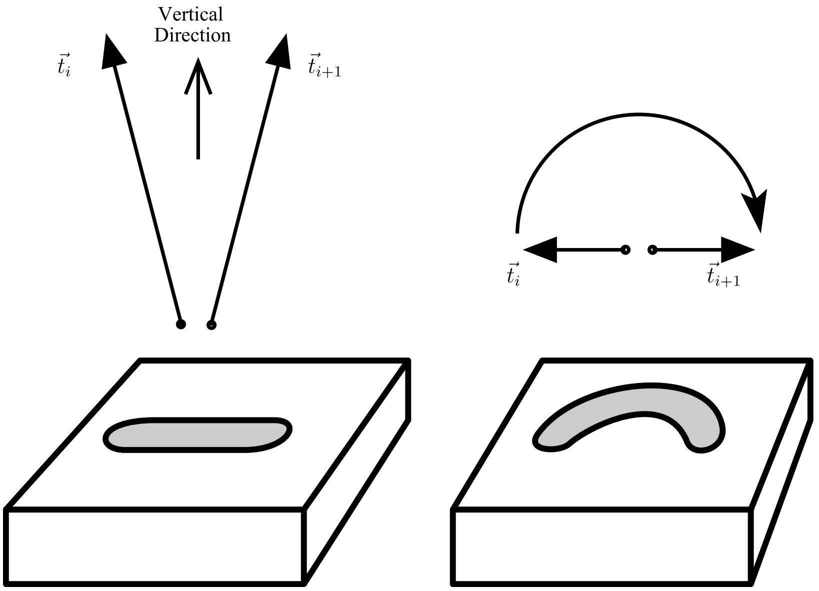

**Fig. 2.** An apparently simple linear motion of a tool (top left, a side view) may be executed as a rotation on some machines (top right, a top view). On the bottom: the difference in cuts between the two motions.

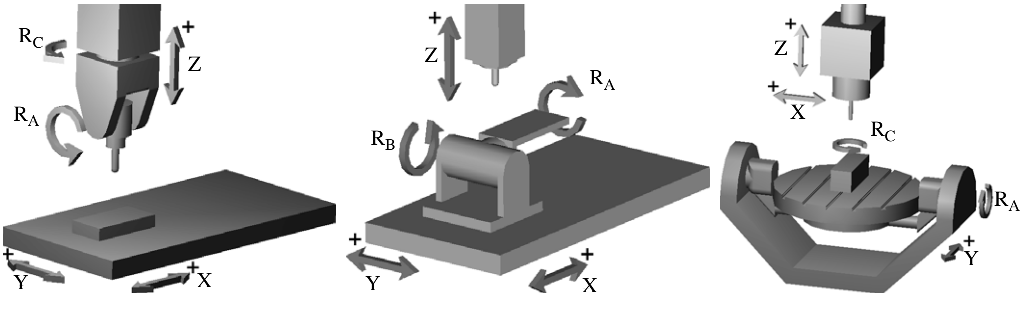

**Fig. 3.** Left: Table spindle. Middle: Titling table. Right: Tilt/rotary. The '+'s indicate the positive direction of motion.

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