

# TRANSLATING MACHINE TOOL ERRORS INTO PART ERRORS ENHANCED VIRTUAL MACHINING FOR SCULPTURED SURFACES

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Sculptured surface machining is a time-consuming and costly process. It requires simultaneously controlled motion of the machine axes. However, positioning inaccuracies or errors exist in machine tools. The combination of error motions of the machine axes will result in a complicated pattern of part geometry errors. On the other hand, little progress has been made in qualitatively translating the machine tool errors into the part geometry errors in the research community. Therefore, in order to quantitatively predict the shape errors of the sculptured surfaces from the machine tool errors, the enhanced virtual machining framework integrates machine tool error models into NC simulation so that part errors can be predicted and shown on a graphic output by simulating the cutting process. It is defined as an “enhanced” system because the virtual part includes information on part geometry errors contributed by machine tool errors when compared with the perfect-cut part geometry obtained by current virtual machining techniques.

In principle, a machining process (removing the material from the stock) can be simulated by taking the Boolean difference of the tool swept volume from the stock. Two different cutting tools, flat-end and ball-end tools, are often used in sculptured surface machining. Therefore, the swept volume model for these two cutting tools are developed. Based on the envelope theory, the task of computing the swept volume can be further reduced to determining the boundary surface of the swept volume, frequently denoted as the envelope surface. For a cylindrical flat-end tool, the boundary surfaces of the tool can be decomposed into the cylindrical surface and top and bottom discs. For ball-end tools, the boundary surfaces of the tool can be decomposed into the cylindrical surface and the top disc and the bottom semi-sphere. The parametric equation for the envelop surface swept by these boundary surface were then derived based on the geometry, trajectory and the orientation of the cutting tool. This parametric form can be used in scan-rendering or forming an approximate polyhedron in machining simulation. For every complete tool path (i.e. one NC block), the tool swept volume is generated and subtracted from the stock, yielding the updated part geometry with the corresponding material volume removed.

Generally, the cutting path for sculptured surfaces is composed of a sequence of linearly interpolated movements. However, due to the machine tool volumetric errors, instead of being straight line as designed, the actual tool path will be a nonlinear motion. The geometric errors  $VE$  and tool rotational errors  $RE$  of five-axis machine tools can be written as  $VE = F(X, Y, Z, A, B)$ , where  $X, Y, Z$  are the nominal motions of machine linear slides,  $A$  and  $B$  are nominal rotations of machine rotary axes. These arguments of  $XYAB$  will change as the cutting tool moves along the designed tool path. Therefore, the ideal cutter path in the NC

program for surface machining is discretized and multiple straight lines are used to approximate the actual path. For each newly interpolated cutter location, the machining errors are predicted from the machine tool error model. After the machine tool volumetric errors have been superimposed on the ideal tool path to generate a series of sub-paths, the tool swept volume can be computed as the Boolean union of the swept volumes created by these discretized sub-paths. As the straight-line sub-paths are used to approximate the curve of the actual tool path, the equations describe the envelope surface created by each straight-line tool path can be further simplified.

The next step in geometric simulation of the machining process would be the conversion of the analytic form of tool swept volume into computable graphic object, such as an approximation of polyhedron. This polyhedral approximation of the swept volume is then converted into pixel data by the scan-line conversion algorithm in computer graphics. After the tool swept volume has been converted into pixel data, the workpiece stock model is built by constructive solid geometry (CSG) modeling and converted to pixel data, too. Finally, the machining process can be simulated by carrying out Boolean subtraction of the tool swept volume from the stock model. Fig. 1 shows the general solid-based machining simulation approach for the enhanced virtual machining system.

The solid modeling approach has the advantage of capturing all the errors including the machine tool geometric errors and the approximation errors in the cutting path generation. However, the solid modeling approach has a few down sides. The very complex geometries swept out by the cutting tool impose a heavy burden on computing resources. With the tool path further broken into sub-paths, the computational problem for CSG-based solid model systems will become out of control since the calculation time is estimated to increase as  $O(N^4)$  ( $N$  is the number of tool path segments) for general tool movements. Also, the comparison between the finished workpiece and the designed part is difficult. Small machining errors (e.g. less than 100  $\mu\text{m}$ ) are unlikely to be detected by a visual inspection of the 3-D solid image. Therefore, based on these observations, a surface-modeling based approach is proposed to quickly simulate the machining errors of sculptured parts. The surface modeling approach approximates the actual cutter contact points by calculating the cutting tool motion and geometry. The approximated part geometry errors contributed by machine tool errors can be written as the functions of cutting tool radius, machine tool volumetric errors and cutting tool orientation errors. Color-coded images are used to visualize and evaluate machining errors, where green means perfect cut, blue means overcut and red means undercut.

Finally, a sculptured surface machined by a five-axis machining center is used to demonstrate the methodology of enhanced virtual machining with error representation. Both the solid modeling approach and the surface modeling approach are used to present the machining errors for sculptured surface. By means of the solid modeling approach, the machine tool error model is integrated into the MasterCAM software package. The final result of the machined surface with machining errors incorporated is shown in Fig. 2. Because the machining errors are very small compared with the overall part geometry, they can not be clearly visualized. Therefore, all the errors are exaggerated by 100 times and presented in Fig. 2. A standalone

computer program is developed to render the machining errors into color-coded image by the surface modeling approach. Figure 3 shows the color-coded images indicating both the undercut and overcut machining errors. These simulation results show that the machine tool error model can be effectively integrated into sculptured surface machining to predict part geometric errors before the physical cutting happens.

In summary, this research work provides the quantitative way to translate machine tool errors into part geometric errors. It integrates machine tool metrology into the CAD/CAM system so that quality assurance can be accomplished in the virtual domain.

### ACKNOWLEDGEMENT

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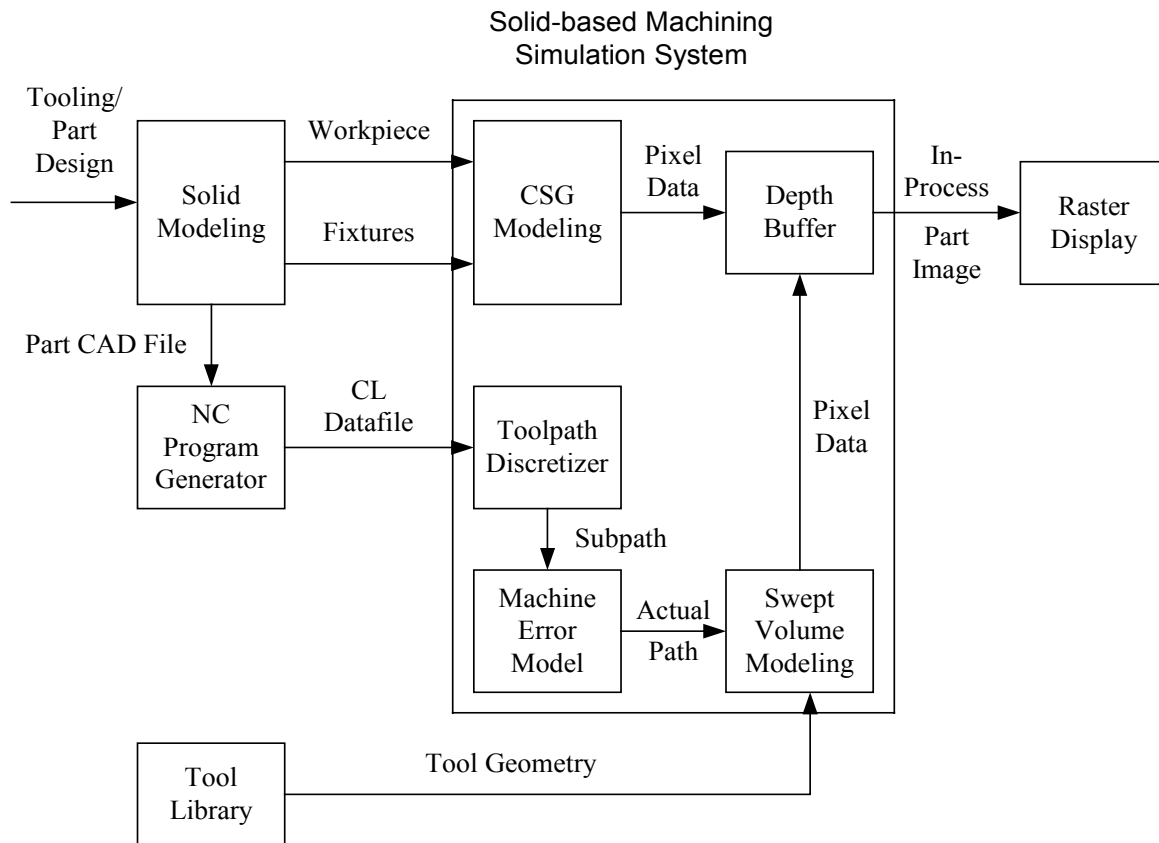


Figure 1. Solid Based Machining Simulation System

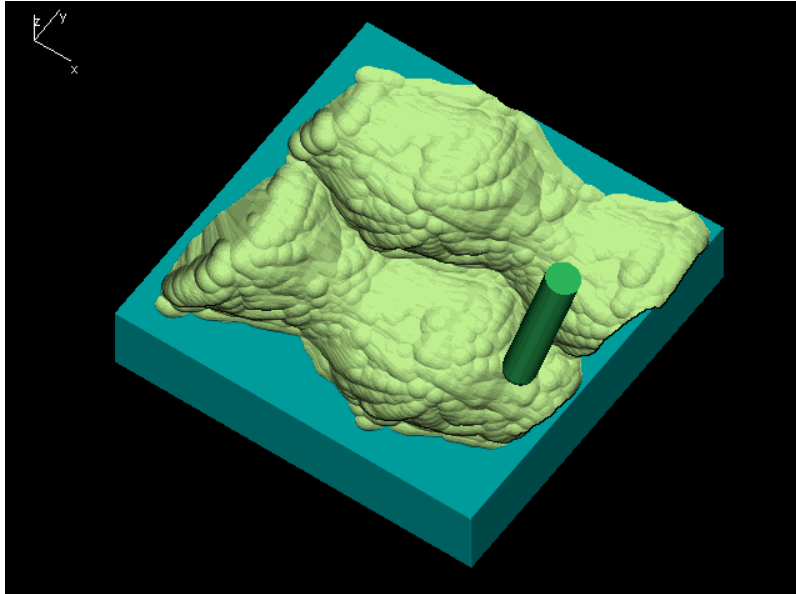


Figure 2. Machined Surface with Machining Errors (Exaggerated by 100 times)

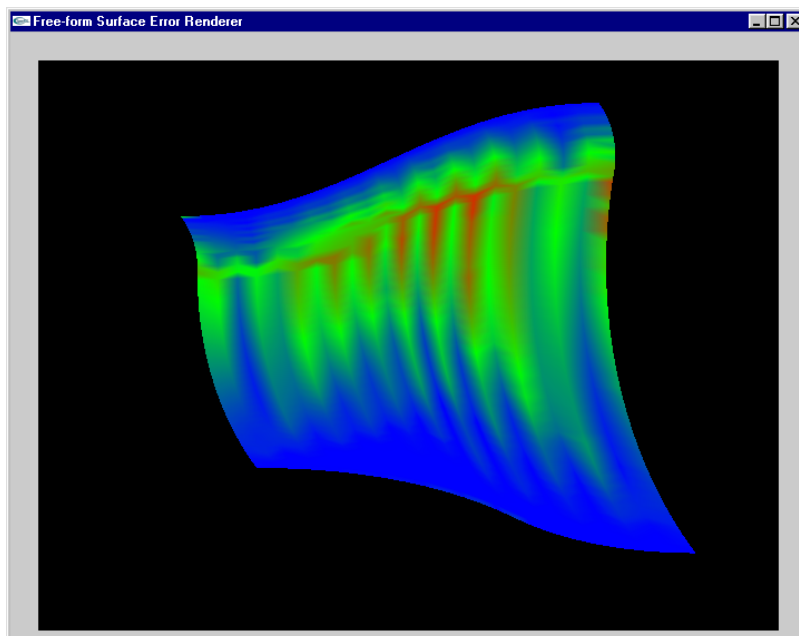


Figure 3. Color-coded Image for Machining Errors  
Green: Perfect Cut, Red: Under Cut; Blue: Over Cut