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Virtual process systems for part machining operations

Y. Altintas (1)[a,*], P. Kersting[b], D. Biermann (2)[b], E. Budak (1)[c], B. Denkena (1)[d], I. Lazoglu (2)[e]

[a] Manufacturing Automation Laboratory, University of British Columbia, Canada
[b] Institute of Machining Technology (ISF), Technische Universität, Dortmund, Germany
[c] Manufacturing Research Laboratory, Sabanci University, Istanbul, Turkey
[d] Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität, Hannover, Germany
[e] Manufacturing and Automation Research Center, Koc University, Istanbul, Turkey

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ABSTRACT

This paper presents an overview of recent developments in simulating machining and grinding processes along the NC tool path in virtual environments. The evaluations of cutter–part-geometry intersection algorithms are reviewed, and are used to predict cutting forces, torque, power, and the possibility of having chatter and other machining process states along the tool path. The trajectory generation of CNC systems is included in predicting the effective feeds. The NC program is automatically optimized by respecting the physical limits of the machine tool and cutting operation. Samples of industrial turning, milling and grinding applications are presented. The paper concludes with the present and future challenges to achieving a more accurate and efficient virtual machining process simulation and optimization system.

1. Introduction

The current trend is to develop digital models of the manufacturing chain from conceptual design to engineering analysis and manufacturing processes. Conceptual design has been practiced since the 1960s with the introduction of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) methods. Engineering analysis has also accompanied design via Computer Aided Engineering (CAE) tools such as Finite Element (FE) Analysis. The concept of digital machines has also been widely implemented in industry by utilizing computer graphics and animation technologies. Machine tools are designed using solid models with integrated FE analysis systems that predict the mode shapes and their dynamic stiffness at the cutting tool–workpiece interface, which leads to a prediction of the machine's maximum material removal limits during design [5]. The geometric removal of material on a machine tool is graphically simulated to check the collision and kinematic correctness of the tool path. Virtual geometric simulations of the material removal and machine tool motions are now commonly used in industry. The dynamics of the servo drives, trajectory generation, tool change and part handling mechanisms are simulated in virtual environments [15]. The interaction between the manufacturing processes and machine tools has also been analyzed using digital models as presented in [1,5,31]. However, the virtual machining of parts by considering the physics of the manufacturing processes has recently been evolving, and the progress being made in this field is subject of this keynote paper.

The virtual machining concept is illustrated in Fig. 1. The CAD model of the part is used to generate NC programs in a CAM environment where the process planners design tool path strategies and select cutting conditions based on their experience.

The NC program is tried on a physical machine, and if the process is found to be faulty, the trial and error cycle between the CAM and physical machining steps is repeated until a satisfactory result is obtained. The aim of the virtual machining is to reduce or even eliminate physical trials by simulating the physical operations in digital environments ahead of costly production as introduced by Altintas in 1991 [13]. There has been progress toward virtual machining by simulating the cutting forces and optimizing the feed along the tool path in three-axis peripheral [76,131] and three- [74,91] to five-axis ball-end milling of dies and molds [104].

The virtual machining system requires sound mathematical models of metal cutting and grinding processes, the dynamics of machine kinematics and CNC servo drives, and cutter–part geometry engagement conditions along the tool path. The mechanics [20,82] and dynamics of cutting [16], drilling [123] and grinding [34,121] processes have been investigated for almost a century, and the progress in their mathematical modeling has been reported in the cited keynote papers and will not be repeated here. This paper presents the integration of cutting and grinding process models into CAM systems for the simulation of part machining operations in virtual environments.

Henceforth, the paper is organized as follows. The identification methods for tool–workpiece engagement conditions along the tool path are summarized in Section 2. The computationally efficient mathematical modeling of metal-cutting and grinding process mechanics that are relevant to virtual machining are presented in

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[*] Corresponding author.

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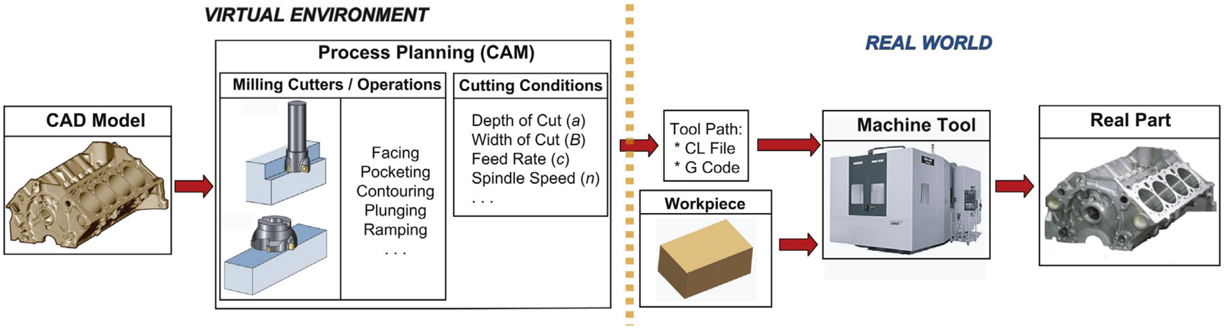

Fig. 1. Architecture of a virtual machining system (UBC MAL).

Section 3. The kinematics and dynamics of machines that govern the relative motion between the tool and workpiece are given in Section 4. The optimization criteria for NC programs are given in Section 5 with the presentation of industrial applications in Section 6. The paper concludes by highlighting the current research challenges that need to be resolved before fully utilizing manufacturing process simulation and optimization tools in CAM environments.

2. Tool–workpiece-engagement identification algorithms

Machining process simulation and optimization requires the geometric modeling of the engagement of the cutter with the workpiece at discrete intervals along the tool path [116,117]. The cutter–workpiece engagement (CWE) will lead to the variation in chip thickness, and axial and radial depth of cut which are needed to evaluate force [11,27,115], torque, power, vibration [98,99] and other process states along the tool path [68,134]. Various geometric modeling techniques are known in the literature for the description of the engagement between a tool and a workpiece, which are reviewed as follows.

2.1. *Solid-model-based systems*

Solid modeling techniques, such as Constructive Solid Geometry (CSG) or Boundary Representation (B-Rep), are used to model three-dimensional objects [108]. These techniques were designed in the mid-1960s when CAD/CAM-systems required models containing the geometric dimensions of the parts.

The method of describing solid objects by their boundaries, i.e., surface patches, edges and vertices, is called B-rep [26]. It supports various mathematical descriptions [77] such as Bézier, Spline, or NURBS (NonUniform Rational B-Splines) techniques [72]. B-rep offers design flexibility and high reproducibility of free-form surfaces [26], and allows a continuous and accurate representation of the sweep volume [130] of a moving cutter envelope as shown in Fig. 2 [57,133]. However, the computation of the intersection between the represented surfaces (Fig. 2d) is a difficult and computationally time-consuming task.

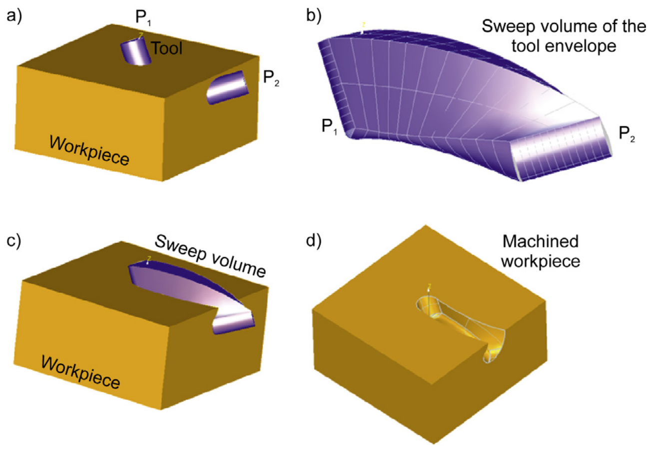

Fig. 2. Example of a boundary representation of a tool-workpiece engagement. (a) Initial (P1) and final (P2) configuration of the cutter. (b) Sweep volume of the moving cutter envelope. (c) Raw stock material and generated sweep volume. (d) Result of the Boolean operation of the sweep volume and the raw stock material [133].

In contrast to the B-rep technique, the CSG (Constructive Solid Geometry) representation allows an easy description of the composition of individual components [72]. The idea of the CSG technique is to combine solid objects, e.g., spheres, cones, cuboids, using Boolean operations, like union, difference or intersection as shown in Fig. 3 [1,128].

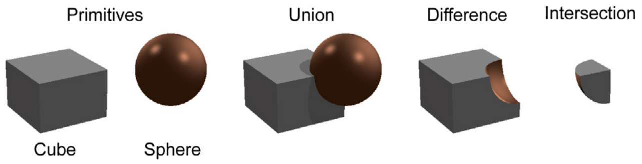

Fig. 3. Example of a CSG-based composition: combining two primitives (here: cube and sphere) using set operations: union, difference, and intersection respectively (ISF).

2.2. *Wire-frame-based systems*

The shape of a 3D object can also be represented by points and lines. These models do not provide any information about the inside and outside of the component, but allow a fast and simple visualization of the components as shown in Fig. 4, although not as smooth as in solid model representation of parts.

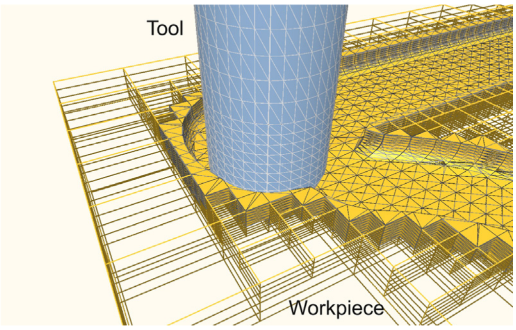

Fig. 4. Example of a wire-frame-based system: The tool and the workpiece are depicted by lines (ISF).

2.3. *Voxel-, dexel-, and Z-buffer-based systems*

Modeling techniques based on z-buffer, dexels or voxels are discrete representations of objects [72]. Using a voxel-based system, the volume is approximated using small, uniform cuboids (Fig. 5) which are called voxels (volume element/volumetric pixel). Voxels are either filled with a material or kept empty. Since the number of voxels (n) depends on the resolution by $O(n^3)$ [128], the drawback of this easy-to-implement modeling technique is a high demand of memory and computation time when the resolution of the model is increased.