Machining processes simulation with the use of design and visualization technologies in a virtual environment

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Abstract: The development of PLM systems is closely related to the integration of the design process with the actual manufacturing process and the complete assessment of the operation at an early stage of the program development. Currently a lot of progress has been made on the application of Virtual Reality tools in the various stages of product development. Aim of this work is the integration of virtual environments with production design processes. Most of the existing systems are focused on the study of the machining process kinematics and do not provide information related to the process results. A production processes simulation system was developed for the determination of critical quantitative and qualitative processes parameters. The system provides realistic visualization of the processes in a three dimensional virtual machine shop environment, walk/fly through and interaction capabilities. System user acquires information related to the process simulated in the virtual environment in real time.

Keywords: Virtual Manufacturing, Surface Roughness, machining processes simulation
1 Introduction

The design of the production processes mainly employs two types of systems. Production processes simulation tools, based on CAM systems and quantitative data determination tools, based on arithmetic, analytical and experimental algorithms. CAM systems have limitations such as lack of providing quantitative data and data related to process feasibility [1]. Most of them have trivial visualization capabilities. Quantitative data determination tools also have limitations. Most of them are not integrated with CAM systems and they provide trivial visualization capabilities.

The development of PLM systems is closely related to the integration of the design process with the actual manufacturing process and the complete assessment of the operation at an early stage of the product development. Currently a lot of progress has been made on the application of Virtual Reality tools in the various stages of product development. Most of the existing simulation systems are focused on the study of the machining process kinematics and do not provide information related to the process results. Aim of this work is the integration of virtual environments with production design processes. A production processes simulation system was developed for the determination of critical quantitative and qualitative processes parameters. The system provides realistic visualization of the processes in a three dimensional virtual machine shop environment with walk/fly through and interaction capabilities. System user acquires information related to the process simulated in the virtual environment in real time. The system extends CAM systems’ capabilities, by intergrading CAM system functionalities with quantitative data determination models in a three dimensional virtual environment. The system could be used for the verification of machining processes and as an educational tool, because of the realistic graphics environment in which the machining processes are simulated.

2 Literature review

In this section systems similar to the proposed are described, that is systems for machining processes simulation in virtual environments. Iowa University [2] has developed a system for machining processes simulation in a five axes CNC machine. The system aims at the improvement of the workpiece machined surface quality by improving cutter path. Ko et. al. [1] have developed a Virtual Manufacturing system for the determination of optimum feedrate values in 2.5 machining processes that provides the ability to determine cutting forces in order to improve the machined surface quality. Qui et al. [3, 4] have presented a Virtual Reality system for material removal simulation that provides information about the required time for the accomplishment of the machining process and quantitative data like cutting forces, surface roughness, required energy and cutter wear. Bath University [5] has developed a simulation system for several types of machining operations that could be employed for design, modeling and implementation of production plans in the virtual environment, aiming at errors detection in the executed operations. University of Patras, [6] has developed a virtual machining operations environment for operations design and training. Yao, et al. [7] have developed a machining operations virtual simulation environment that provides capabilities for dimension measurement, in order to determine the processed part precision and to measure final surface quality parameters. Peng et al. [8] propose a desktop VR environment to explore the machining process element of CAPP. Spence et al. [9] are
Machining processes simulation with the use of design

developing a multi-axis machining process simulation program with a special sweep representation for Boolean part model updating. Jang et al. [10] develop a voxel-based simulator for multi-axis CNC machining to model efficiently the state of the in-process workpiece, which is generated by successively subtracting tool swept volumes from the workpiece. Lin et al. [11, 12] developed a virtual reality training system to determine the impact of the simulated industrial accident on decision-making performance in a real machining task. Yi et al. [13] presented a computer simulation approach to machining a gear and cam by using a virtual orthogonal 6-rod machine tool. Weinert et al. [14] developed a virtual manufacturing system for the determination of chip thickness throughout the machining process, for quantitative data calculations such as the cutting forces. The outcome of the European research program Virtool [15] is a graphics environment, in which Virtual Reality techniques are employed for training and evaluation of qualitative and quantitative parameters related to the simulated machining process. Montana University [16] has developed a lathe simulation system for training applications. The process parameters are the input to the system and the material removal is being simulated for the part production. Wang et al. [17] developed illumination models in a virtual machining environment for chip simulation. Manufacturing Engineering Laboratory [18] developed a Virtual Reality platform for universities and companies collaboration. In the field of machining the octahedral hexapod machine tool at NIST is being simulated [19] for the implementation of verification tests related to the machine performance, the improvement of the machine control system, etc. Jonsson et al. [20] describe the structure and implementation of a virtual reality concept for real-time simulation and visualization of water jet cutting machine.

3 Virtual Environment for machining processes simulation

Aim of this work is the integration of virtual environments with production design processes. A machining processes’ simulation system has been developed for real time visualization, verification and qualitative and quantitative data determination related to the process simulated in the environment. The structure of the system is shown in figure 1. Virtual environment has been developed using commercial software tools. The structure of the virtual environment is shown in figure 2. A complete machine shop has been visualized and the functional characteristics of a three axes CNC milling machine are being simulated.

The virtual environment has the following functional characteristics:

- Objects behavior is as realistic as possible.
- User has the ability to interact with all the objects in the virtual environment.
- User selects cutter from the cutters table and it is installed automatically in the CNC machine spindle.
- User selects workpiece from the workpiece table and it is installed automatically in the CNC machine worktable.
- During machining process simulation, CNC machine axes and cutter animate in a realistic way.
Workpiece material removal is being visualized in a realistic way during machining process simulation.

Machining process information like the G code command simulated in the CNC machine, feed, spindle speed and cutter path are visualized in a special table.

User can pause, stop or restart the machining process.

When the machining process is finished, quantitative data and graph charts for the process are visualized, according to user preferences.

In figure 3 the virtual environment for machining processes simulation is presented.

Figure 1  Structure of the machining processes simulation system

Figure 2  Structure of the virtual environment for machining processes simulation
3.1 Virtual environment software modules.

The following modules of the environment have been developed and integrated in the employed Virtual Reality platform for the implementation of a machining processes simulation environment:

- Geometrical models visualization: Models developed in CAD like machine shop building, machines, etc., dynamic geometry models like the workpiece, 3D text, etc., virtual models visualization characteristics, like color and texture.
- Geometry models hierarchy, constraints, interaction attributes.
- CAM system integration.
- Cutter path determination according to the G code program.
- CNC machine axes animation.
- Cutter animation.
- Workpiece material removal visualization during machining processes simulation.
- Quantitative data determination.
- Verification checks during machining processes simulation.

Following, the most critical software parts are being described.

![Figure 3](Virtual Environment for machining processes simulation)

3.2 Workpiece definition

Workpiece geometrical model is defined as a polygons mesh with the use of virtual environment dynamic geometry tools that provide the ability to change the shape of the model in real time. The use of dynamic geometry is necessary, in order to visualize the workpiece material removal during machining processes simulation.

In figure 4 the algorithm for the definition of the workpiece polygon mesh is shown. In figure 5 the workpiece is shown in the virtual environment in wireframe and shaded mode.

3.3 CAM system integration.

CAM software tools are used for CNC programming. The produced G code programs are exported by the CAM system in a text format file. In order to integrate the virtual machining processes simulation environment with the CAM system, the G code program
is the input to the environment. The software tool integrated in the virtual environment reads the G code file and its data are converted and imported to the environment in a format suitable for further editing.

**Figure 4** Algorithm for the definition of the workpiece polygon mesh

**Figure 5**

(a) Workpiece in wireframe mode

(b) Workpiece in shaded mode

3.4 **Cutter path determination.**

Following the G code file import to the system, the path of the cutter is determined. Each G code command define a linear or a curvilinear movement of the cutter in the three dimensional space. A software tool has been developed that converts G code data into geometrical equations for linear and curvilinear trajectories in three dimensions, to define cutter path. These equations are used for the simulation of CNC machine axes movements in the virtual environment. If compensation has been defined in the G code program, offset trajectory is being determined, with the use of appropriate geometrical equations. The intersection point is calculated for each two adjacent trajectories, to determine start point for the next movement. Then, the equations for linear or curvilinear movement are employed.

3.5 **Workpiece material removal.**

For the simulation of the machining process in the virtual environment, workpiece material removal should be visualized in real time. Cutter removes material when it intersects the workpiece. The material that is removed is the intersection volume between these two objects, at each cutter position. For the visualization of the material removal on the workpiece, the intersection with the cutter has to be determined along the cutter path. Material removal is visualized in the workpiece by altering its polygon mesh vertices coordinates, according to the intersection with the cutter, at each cutter path position.

In the algorithm that was developed:
• The cutter is assumed cylindrical.
• Cutter and workpiece intersection is determined in differentiated path positions.
• Intersection is determined by comparing coordinates between workpiece polygon vertices and lower cutter cross-section.
• Workpiece vertices inside the cutter volume decrease their Z coordinate to the minimum Z coordinate of the cutter.

In figure 6 the visualization of material removal in the virtual environment is shown. In figure 7 the algorithm for workpiece material removal visualization is shown.

3.6 Quantitative data determination.

The virtual environment for machining processes simulation provides quantitative data for the machined surface roughness. Roughness in machining is a parameter related to the geometrical characteristics of the abnormalities produced by the cutter in the machined surface. The size, shape and topomorphy of these abnormalities in the machined surface depend on [21] machining parameters like: cutting speed, feed, cutting depth, etc., geometrical characteristics of the cutter, like cutter nose radius, rake angle, side cutting edge angle and cutting edge geometry, workpiece and tool material combination and their mechanical properties, quality and type of the cutter, jigs, fixtures and lubricant used, vibrations between the cutter and the workpiece.

There are several parameters for surface roughness measurement that provide different information for the measured surface. Surface roughness is measured in areas of the machined surface, selected by user and measurements refer only to the selected area. Thus, in a machined surface, measurements must be made in more than one area. Usually linear or radial measurements are taken. Linear measurements are made in line or vertical to the feed direction for a specific distance. Radial measurements are made around a fixed point for a specific angle.

A model has been developed for the machined surface roughness parameters determination. The model is divided in two parts:
• The determination of machined surface topomorphy.
• The calculation of the surface roughness parameters, according to the surface topomorphy.

In the model, parameters like cutting speed, feed and cutting depth, cutter diameter, height, cutter type, number of teeth and cutting edges geometry that contribute in surface roughness formation are considered. Parameters that contribute in the surface roughness formation, like cutter material, quality and type of the cutter, quality of jigs, fixtures, the use of lubricant, vibrations in the machining process are not considered.
3.6.1 Determination of machined surface topomorphy.

The model for the determination of the machined surface topomorphy has been implemented in a three dimensional graphics environment developed in OpenGL (fig. 8). In this environment the motion of the cutter relative to the workpiece is simulated. The motion of the cutter is based on the cutting conditions defined in the G code file. During the motion of the cutter, the sweep surface of its cutting edges is determined. For the determination of cutting edges sweep surface during machining simulation, the cutter is being modeled, according to the shape and number of its cutting edges (fig. 9). Cutting edges shape is defined from the outer edge profile of each cutting edge, which defines the overall cutter profile. Each cutting edge is approximated by equal elementary sections that are straight lines (fig. 10).

The produced sweep surface has overlapping triangles, since part of each cutting edge sweep is being overlapped by the next cutting edge sweep or the next cutter pass sweep. If the cutter sweep surface is projected from its down side, the final machined surface topomorphy is derived, since the overlapped triangles are not visible in this projection, due to the hidden line algorithm, that projects to the user only the geometry visible in each point of view. This final machined surface topomorphy is derived from this projection in the form of cloud of points. The coordinates for the cloud of points are determined. The pixels within workpiece limits visualize the machined surface. These pixels are converted into X and Y coordinates in the graphics environment coordinate system. Z coordinate is derived from the visualization system Z buffer.
The cloud of points coordinates describing the machined surface topomorphy are exported in a text file and used to calculate quantitative parameters for the machined surface roughness in the virtual environment.

3.6.2 **Calculation and visualization of surface roughness parameters in a virtual environment.**

In real environments surface roughness measurements are carried out in surface regions, selected by user. In the developed system this procedure is being simulated in the virtual environment. A table has been developed for surface roughness quantitative data visualization (fig. 11). On the upper part of the table the measurement region on the workpiece machined surface is defined. On the lower part of the table the selected surface region topomorphy and the respective surface roughness parameters values are being visualized.

For the determination of the measurement region, a handler has been developed (fig. 12). System user defines the position of each handler end. Handler ends define surface roughness measurement area limits. Handler defines a vertical to the machined surface plane, in which topomorphy will be determined and surface roughness parameters will be calculated from this topomorphy.

For surface roughness parameters determination, cloud points near the vertical measurement plane are retrieved from the file. Cloud points used in each calculation are connected with straight lines in the vertical measurement plane to produce surface topomorphy for this region in the virtual environment. In the virtual environment surface roughness parameters and surface topomorphy mean line are calculated. In the quantitative data table, surface topomorphy and mean line are visualized in a specially developed diagram and also surface parameter values are shown. User has the ability to create a machining process report in the form of a text file (fig. 13). In the machining process report file surface roughness data for the measurement region are stored and could be acquired for further use. This process can be repeated in any other region of the machined surface.

**Figure 8** OpenGL machining processes simulation environment for machined surface topomorphy determination
4 Machining processes simulation pilot case.

In order to acquire results from the system, a user performs the following actions:

- A workpiece has to be created and a cutter has to be selected.
- Cutter path has to be produced in the form of differentiated points in a text file. In the file, differentiated points coordinates are defined in the machine coordinate system.
- Machining process is simulated in the virtual environment.
- The file with the differentiated cutter path points is opened in the OpenGL machined surface topomorphy determination software tool.
- Machining process is simulated in the OpenGL environment.
- Surface topomorphy is exported as a cloud of points in a text file.
- This file is being read in the virtual environment, to visualize surface topomorphy graph and to calculate surface roughness parameter values for the measurement area selected by the user.

User has to select surface measurement area in the virtual environment quantitative data table by setting handler ends positions, either by direct interaction with the geometrical models or by the two sliding handlers in the quantitative data table, defining measurement area. Then, by pressing “Calc” button, surface topomorphy appears in the corresponding graph. In the surface topomorphy graph mean line is shown (a horizontal blue line). Also the system calculates surface roughness parameters for this topomorphy and shows their values in the quantitative data table (fig. 11). User can move the handler (change its position, orientation or length) and take measurements in different areas of the machined surface. This feature is necessary since it is usual in real surface roughness measurements to place the profiler contact element in a position and measure roughness radically from this position at a fixed radius for a specific angle (usually 180° or 360°).

The system has a feature for the creation of a machining report in the form of a text file by pressing “Save” on the quantitative data table. The system calculates and stores in
this report data related to the G code file used for simulation, the selected cutter, the selected workpiece and surface roughness parameter values for the measurement position are given every 10° degrees for a full round. In figure 13 an example machining report is given.

5 Conclusions

The main aim of the proposed system is the integration of virtual environments with production design processes. The system extends CAM system capabilities, since it provides higher level visualization functionalities and quantitative data for the production process defined in the CAM system. A new method based in OpenGL programming language is proposed for machined surface topomorphy determination in order to calculate critical quantitative data affecting machined surface roughness. The system could also be used as an education tool since machining processes are realistically executed in the virtual environment. The proposed research contributes in the creation of critical mass contemplations for future research directions. Research evaluation will lead in critical conclusions related with the required production processes simulation systems characteristics and their potential use in real industrial environments. Moreover the proposed system could be further developed to provide additional characteristics and functionalities, could be extended in other machining operations or even other industrial processes.

Currently there is a tendency for Virtual Reality characteristics and production processes models integration. This tendency is leading to the creation of the next generation simulation systems that will provide quantitative data for the process, increased visualization, fly through and interaction capabilities in a virtual environment. The research is this area is showing adequate maturity but the final form of these simulation systems for use in real industrial environments has not yet been delimited, although significant systems have been presented.

Figure 11 Virtual environment quantitative data table
Figure 12 Measurement area determination with the use of the handler
Figure 13 Machining Report example

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