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# 6-axis CAM toolpath planning for 3D-optics

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**Abstract**
The CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) toolpath planning for 3D ultra-precision machining is one main aspect of the production for complex 3D optical components. ModuleWorks and ZEISS are working together to develop new machining cycles for an integrated process chain that enables optical parts to be machined using a single CAD/CAM system. Ultra-precision machining is used for parts that need to be machined to an accuracy of just a few µm and a roughness in the range of nm. Optical parts require both types of machining, ultra-precision machining for the optically effective areas of the part and conventional machining for the non-optical areas. Until now, no single CAD/CAM system combines both types of machining in a single, integrated solution. The paper presents the developed toolpath patterns, which are integrated into ModuleWorks module library, demonstrated under a Rhino CAD software plugin. With the developed toolpath design it is possible to output data for slow tool, fast tool and full 6-axis machining operations. Integrating all machining relevant processes in a unified system is expected to accelerate process programming for cutting complex freeform surfaces and to improve the quality and cost-efficiency of producing ultra-precision parts. The new system is powered by the 64-bit optics kernel and has been specially developed to meet the growing demand for high-precision machining of increasingly complex geometries in the optics industry. Furthermore, the optics kernel supports multi-threading for fast, ultra-precision machining of optical parts such as lenses, molding tools and lens arrays. It supports grinding and diamond turning as well as grinding patterns for roughing, drilling, chamfering, slotting and contouring.

CAD, CAM, 3D-Optics, 6-axis toolpath

## 1. Introduction

CAM systems of today do not support ultra precision machining of optical components, because of their general setup for machining of macroscopic parts. The requirements of ultra-precision manufacturing of optical components with a sub-micron feature size and surface roughness in the nm range cannot be processed within these systems. Specific toolpath and surface feature patterns are needed which are currently only available for parametrically defined shapes like aspherical surfaces and grids (DIN 10110-12 like description forms).

## 2. Requirements for the UPM toolpath planning

UPM (ultra-precision machining) requires a high accuracy of the process chain from CAD-CAM-post-processing to the CNC (Computer Numerical Control) machine [4]. Within the state of the art process chain (see Figure 1) the toolpath generation of various operations are distributed to different CAM-systems, which support specific machining features to either machine the optical effective components or to manufacture molds/tools for replicative manufacturing [1]. To raise the efficiency of the UPM process for complex optical components, it is necessary to be able to define the CAM process in one CAM system environment. Input data is retrieved from CAD-systems (or neutral exchange formats), metrology systems (point could data) or optical design software (parametric descriptions). In our days the UPM process is still programmed in specific CAM systems but the integration for conventional CAM cycles like drilling, facing and chamfering is done with state of the art CAM systems. On the other hand, standard CAD/CAM system do not offer the specific features used in UPM (aspheres, diffractives etc.). Furthermore the feature size of mircostructured optical free-form surfaces [2] is a fraction (1/1000) of the size of conventional CAM features (slots, holes etc.). The desired approach therefore is to have all relevant machining patterns and the geometric feature support in one UPM CAM system.

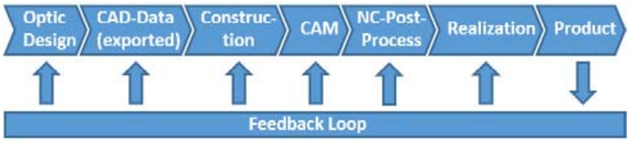

**Figure 1.** CAD/CAM process chain

### 2.1. Geometry types for UPM CAM

As a basic requirement for the development of an ultra-precision toolpath output, the input geometry has to be as accurate as possible. While conventional optical designs are based on parametric input geometries the demand for more complex designs requires a more powerful geometry descript-tion. We address this need by supporting NURBS freeform geometries and point clouds alongside a flexible description of parametric geometries. Typical issues of import data quality, like gaps, cusps or overlaps can only be treated within cut tolerance of the toolpath. Therefore the toolpath [4] calculation can only bridge gaps or defects smaller than the required feature size of the design part.

A parametric part description provides an accurate definition for any toolpath point with best calculation performance. This was the reason why state of the art CAM systems for UPM are focused on these description forms. The parametric geometry is based on a tree that represents the complete formula as entities that describe either base surfaces (such as asphere, torus etc.), modifiers (such as trimming operations or transformations) or combinations (such as superposition, grid layouts).

Point clouds are a standard input from metrology systems and consist of a grid of points which is dense enough to capture all necessary part features. The acquisition and handling of metrology data was part of a founding research project "microAdapt" [3]. The metrology data can also be used as error compensation input for consecutive steps within a grinding process of replication molds, which is called adaption.

### *2.2. Environment for UPM CAM*

As soon the part description is getting more complex than single parametric surfaces, a machine and cutting simulation software is necessary to verify the machining process [2]. The simulation allows a simulation of the machine motions, a collision checking of interacting components and an accurate material removal simulation (see Figure 2).

### *2.2. Development of algorithms for UPM CAM*

Based on the accurate geometry description of the parts, which can be combined from the geometric input types, specific toolpath patterns are being developed. These patterns are dedicated to certain machining strategies like lathe type machining, hobbing and milling.

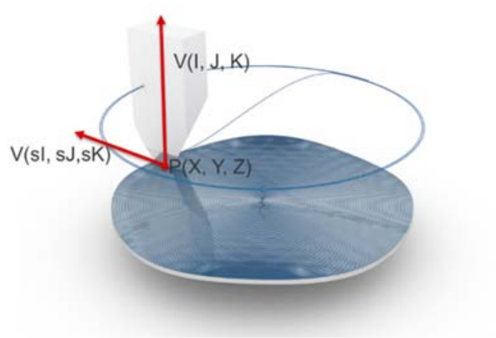

**Figure 2.** Spiral pattern for slow and fast-tool kinematics

## 3. Toolpath patterns and applications

A key factor for the process chain is that all steps address the requirements of UPM. Essential is the initial toolpath calculation step based on the different geometric inputs.

### *3.1. Tool path computation and representation*

The tool path itself has to be as accurate as possible which means that the computation must not rely on any approximations but rather leverage the correctness of the mathematically defined input data. At the same time the algorithms have to be general enough to handle very general input, i.e. geometry and tool types. This leads to solving an optimization problem for every position in the tool path.

Another factor that has direct implications for the quality of the machined surface is the smoothness of machine motion. Therefore multiple patterns were developed to minimize axis acceleration and jerk. In the simplest form this is done by a contour turning tool path for rotational symmetric parts. For non-rotational parts this pattern is extended to accommodate height oscillations thus resulting in a spiral pattern. To ensure an even surface quality the step over of the spiral can be adjusted to the slope of the machining surface. Also $g^2$-continuous linking motions between toolpath slices remove machine vibration and improve the surface quality of the machined part.

For representing the tool path we choose a full 6 axis model which means the tool path stores the tool position and the tool orientation as two orthogonal vectors that describe the tool axis and cut direction for each point in the tool path. This allows to represent all possible tool positions and orientations which is important for complex machine dynamics like multi-axis machining (e.g. B-normal to part surface) and FTS (Fast-Tool-Servo) for highly dynamic 3D shapes (e.g. lenslet arrays).

## 4. 3D tool model

A full 6-axis parametric representation of the tool assembly allows us to take full advantage of collision checking functionality during toolpath calculation. Specifically for multi-axis machining of complex shaped concave parts with steep walls, automatic collision checking during toolpath calculation is a key factor. This can be verified within simulation of the machining operation. Our machine model allows to represent the kinematic tree along with visualization and collision checking geometries. Together with algorithms for 6 axis forward and inverse kinematic this allows to use tool path verification utilities that have proven invaluable for conventional machining also for UPM such as back plotting, collision checking and cut simulation.

## 5. NC posting toolpaths

The last step of a CAx-process chain before real machining starts, is the so called posting of the NC-code. This is also a critical step regarding performance and accuracy of the process chain. The calculated millions of setpoints must be transferred into machine tool specific and syntactically correct output. The fact that the tool path is full 6 axis allows to adapt the NC output to different machines without re-computation. To allow further customization of the NC output to controller specifications or custom needs a scriptable post processing framework for generating NC output was developed, which supports any machine kinematics and generates accurate ($10^{-9}$ mm) and big data files (>50 t [setpoints / s]). On Linux operating system the framework supports toolpath streaming and multi-threading for posting of machining operations, to enhance the performance in the post-processing step, e.g. for FTS output.

## 6. Conclusion and Future Work

Derived from 10 years of research projects we have developed and tested a UPM CAx software package, which allows the programming of complex shaped 3D-optical components within one CAM solution. The developed framework is extensible for future requirements and more toolpath pattern types will be added for 5-/ 6-axis processes.

The integration of UPM specific functionality into a conventional CAM solution by addressing the special needs of UPM throughout the process chain is challenging and requires consistent modelling of the process. However the benefits of being able to program complex shaped geometry including optical functional surfaces within one system can be seen today. This will get even more important for future developments in the light of advanced machining patterns, new 5-/ 6-axis processes and automation in production machining.

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