Manufacturing of Free-Form Surfaces using a Fast Tool Servo (FTS) and an online Trajectory Generator

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Abstract

High-precision and ultra-precision machining are the key technologies in the manufacture of high-precision surfaces with tolerances in the submicron range. In addition to rotationally symmetric geometries, more and more non-rotationally symmetric surface geometries are required. Examples are eye glasses, laser mirrors and micro structured surfaces.

In this context the research activities of the Transregional Collaborative Research Center ”Process Chains for the Replication of Complex Optical Elements” SFB/TR4 of the Universities of Aachen, Bremen and Stillwater (USA) have the objective to lay the scientific foundations for a deterministic and economic mass production of optical components with complex geometries, e.g. aspheric, non-rotational asymmetric or microstructured surfaces eventually superimposed on free-form geometries.

For the manufacturing of free-from surfaces the Fraunhofer IPT has developed different Fast Tool Servo systems (FTS). A PC-based controller is used for set point calculation and for the position and velocity control loop of the drives. For the manufacturing of free form surfaces based on the mathematical description of Non Uniform Rational B-Splines (NURBS) an online trajectory generator was developed [1]. The paper presents the layout of the online tool path calculation as well as results of the manufacturing of a free form surface.

Introduction

In case of using the replication processes injection molding or glass pressing ultraprecision manufacturing of mold inserts is required and precision machining processes like diamond turning and fly-cutting are essential. To manufacture complex lenses with high accuracies the mold inserts must be fabricated with an adapted geometry to compensate form deviations caused by the machining process or typical shrinking effects during the replication process. To determine the suitable geometry of the mold inserts several iterations loops are necessary.

For manufacturing an adapted mold geometry the trajectory generation is fundamental for ultra precision machining. Starting from the given data set of the surface (NURBS data format) the free form surface is analyzed and prepared for the manufacturing process in a Matlab routine. A radius compensation of the diamond tool is considered in this step.

After this the NURBS surface is loaded to the control unit of the Fast Tool Servo. The calculation of the tool path is processed online. Therefore the actual positions of the axis and the spindle of the ultra precision lathe are used for the calculation of the tool path. The tool centre point is calculated online by an optimization routine to detect the positions of the knot vectors and also the position on the surface.

Optic Design

In the following an optical system using a 3-D tailored free-form surface designed by the company OEC AG is presented. 3-D tailoring is a constructive method for the design of free-form illumination optics [2]. Light from a light source is intercepted by the free-form mirror or lens surface and redirected in a way to cast exactly the prescribed illuminance distribution on a target surface. The shape of the surface is found by solving a set of differential equations which connects the continuity of the surface, the desired trimming and the redirection of radiation defined by the slope and curvature of the surface.

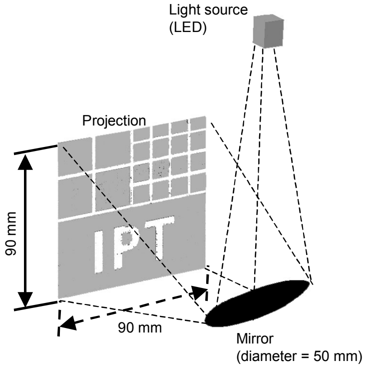

Fig. 1: Illumination Principle.

The sketch in Fig. 1 shows a 3-D tailored free-form mirror which redirects the light from a LED to form the Fraunhofer IPT logo as brighter lines in front of an evenly lit square. This illuminance distribution is produced by means of geometric optics with a single reflection at the free-form mirror surface. The mirror has a diameter of 50 mm. The scaleable illumination has a projection size of 90 mm x 90 mm at this dimensions.

The mathematical description of the given free-form mirror is based on NURBS. Until now a reproducible and competitive manufacturing has not been possible because a convenient data processing for ultra precision machine systems did not exist. Following the state of the art the mirror had to be manufactured by milling and hand polishing. It was the goal of the presented research activities to solve those problems by building up a closed data interface based on the NURBS format to provide adequate surface information for the manufacturing of even complex optical surfaces by ultra precision processes.

Fast Tool Servo Systems

The fabrication of precision molds for rotational symmetric components is one of the domains of diamond turning. Moreover, diamond turning can also be used for microstructuring of molds. Grooves can be generated with diamond knives in a plunge cut turning process or with small radius tools by contouring individual grooves. Quasi-linear structures can be generated by a turning process when large off-axis distances are applied. Asymmetric surfaces with limited deviations from rotational symmetry may be generated by turning using a Fast Tool Servo System.

During the research work an aerostatically guided fast tool servo was used for manufacturing the free-form mirror mentioned above [3]. The supported slide of the fast tool servo consists of CFK (carbon fibre reinforced plastic), in which a permanent magnet is incorporated (Fig. 2). It is driven by a linear motor comprising of two coils, one above and one beneath the slide, which can be cooled by a pipeline system, if that is required. The motor is powered by a current controlled analog amplifier with a maximum current of +/- 8 A.

The position feedback control system is PC-based. A position measuring system and a D/A converter are necessary for basic position control. The synchronization of the set point generator with the turning lathe requires a quadrature counter module for the measurement of the machine axes' rotation angle and feed. The main bottle neck of the PC architecture for feedback control is the PCI bus system. Furthermore it is difficult to measure synchronized signals with three different modules having independent device drivers and interrupt service routines. The demanded design is an autonomous device, which synchronizes signal capturing/conversion and which facilitates bus communication by using one bus access for reading the inputs and one bus access for writing the outputs.

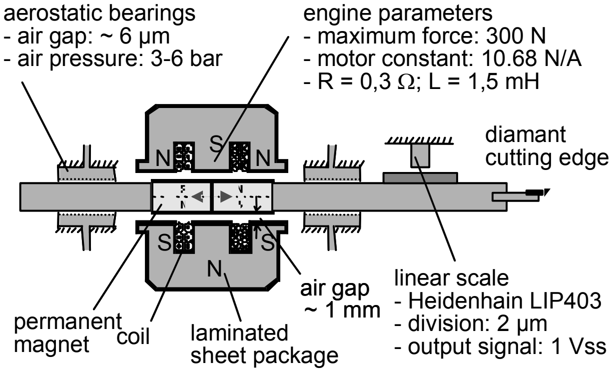

Fig. 2: Schematic drawing of Fast Tool Servo.

Due to the lack of such PCI (peripheral component interconnect) board solutions on the market the required I/O-system was built up on the basis of a PCI prototype board. The developed solution includes a 1024-fold interpolation module for position measuring (Heidenhain IK410) which yields to a resolution of approximately 2 nm with the used LIP403 linear scale from Heidenhain. Furthermore there are two A/D converters, several D/A converters and two quadrature counter modules mounted on the prototype board. The analog I/O ports are build up strictly differential concerning better signal noise ratio. One RISC-type I/O processor is implementing a sync and transfer state machine. The PCI controller includes FIFO (first in, first out) memory for PCI writes and reads providing buffered I/O which is necessary for needing only one bus access per control cycle. The maximum possible control cycle is hardware limited to 40 kHz by the interpolation module latency of 25 µs. The other module latencies just as the interrupt latency are masked out by software design. The employed control cycle typically is in the range from 8 kHz to 25 kHz.

The software of the control system includes the device driver for the PCI I/O board and a server system which facilitates the building of the control algorithm and the set point generator as well as elementary features like online representation of position data. To provide deterministic time response FSMLabs Real Time Linux is used as the operating system. The Debian Linux distribution features a standard Unix environment and a graphical user interface. A control algorithm and a NURBS based set point generator are implemented in Matlab/Simulink whereby the set point generator's memory management is heavily assisted by the aforementioned server system. The applied control algorithm is a cascaded PI/P-controller. The missing actual velocity is generated by differentiation of the actual position. In order to reduce the following error the differentiated set point is added to the set velocity.

Some compensations are introduced to advance the performance of the control system. The magnetic attraction between linear motor and enclosure is compensated by a lookup table measured in the initialization sequence. Since the applied linear scale is an open one, it cannot be oriented perfectly leading to significant errors in the interpolation process. This similarly is adjusted by a lookup table.

For manufacturing of non-rotational symmetric components made of non-ferrous metals as well as components made of steel and hardened steel the Fraunhofer IPT has developed a hydrostatic guided Fast Tool Servo System that uses the control unit mentioned above [4]. Especially for ultraprecison machining, the dynamic exitation of the base machine should be kept as low as possible. Therefore, a system for dynamic mass compensation was necessary for achieving high accelerations of the tool and high precision.

The FTS has two independent slides. One is for the tool movement and the other is for the counter movement to eliminate the dynamic forces caused by the accelerations. Both slides have their own drives, measuring system and control loop. Due to the high bandwidth of the system (> 200 Hz), the design of the slides has a great influence on the translatory inertia of the FTS system. The frames of the slides are made of Aluminium. The permanent magnets for the motors are held by plates made of carbon fibre reinforced plastics. By the use of lightweight materials, it was possible to reduce the moving mass to 1.6 kg. Each slide has two motors, one above and one below the permanent magnet to compensate the attractive forces (Fig. 3). The linear motors are water cooled.

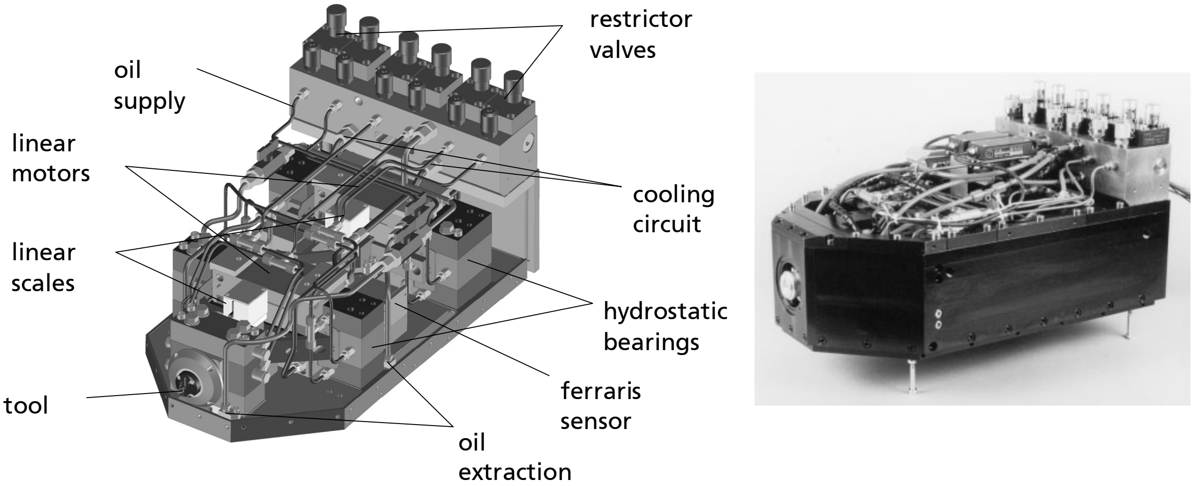

Fig. 3: Design of hydrostatic guided Fast Tool Servo System

The motor is a single-phase moving magnet type, which was specially designed for the FTS system. The FEA-optimized design has a thrust constant of 60 N/A, a resistance of 2.7 Ohms and an electrical time constant of 5.2 ms. Two current amplifiers are used to drive the system. For ultra precision turning of non-ferrous metals, an analog amplifier with a intermediate voltage of 50 V is used. A switched amplifier, having an intermediate voltage of 200 V, has been chosen for machining steel.

With a total mass of 1.6 kg for the slide, the theoretical maximum jerks are 134,000 m/s³ (analog) and 536,000 m/s³ for the switched amplifier. For a 8 mm accelerated/decelerated stroke, with maximum jerk, this results to a maximum velocity of 1.29 m/s and a minimum time of 12 ms (analog), resp. 2 m/s and 7.8 ms for the switched amplifier.

For sinusoidal motion, the maximum frequency depends on maximum jerk, maximum velocity, and maximum stroke. Full stroke (8 mm) is available for frequencies below 32 Hz, first order limited stroke up to 64 Hz (4 mm) for the analog design and 130 Hz (2 mm) for the switched design. The switched amplifier design can produce sine strokes of 300 µm at 300 Hz.

A square wave can be treated as Fourier series decreasing, first order amplitudes. Using a 7th order Fourier approximation, possible frequencies are 32 Hz for full stroke and up to 150 Hz (1.5 mm) the first 1st order limited stroke. In reality the thermal limits of the amplifiers and the motor will limit the maximum continuous strokes.

Trajectory Generation of Free-Form Surfaces

The online computation of NURBS based tool paths on a fast tool servo are possible in different ways. The necessary calculating time is limited. With an 8 kHz position control clock every 125 µs the input and output has to be transferred from and to the I/O board and the actual computing has to be completed. The I/O operation and the PI/P feedback control take maximally 30 µs. 95 µs remain for set point generation.

In the present case the fast tool servo controller is PC based (Pentium III, 650 MHz). The Intel Pentium processors are typical representatives for the CISC (Complex Instruction Set Computer) architecture, i.e. they are optimized as workstation computers and have a huge instruction set with many data types and access alternatives. They can hold huge amounts of data in several Giga Byte main memory and can handle virtual memory simultaneously of many programs.

The basic technique to efficiently process CISC instructions depends on heavy pipelining. The instruction is not handled in one step, but passes through several sub processes like instruction fetch, decode, get data, process data, write back data. The pipeline never empties, i.e. after fetching of the first instruction this instruction is decoded and the next instruction is fetched at the same time. The other sub processes behave similarly. To remain economically priced the large main memory is decoupled from the processor with a hierarchy of even faster and in that order higher priced and thus smaller cache memories. That way the CPU can in spite of external waiting cycles in the majority of cases work on the internal cache. Task switches are performed with a combination of hardware and software. If a task switch occurs, the task state, i.e. the processor registers, will be saved in the respective task context.

The pipelining, caching and hardware/software task switching of CISC processors unfortunately show a non-deterministic time response. For instance depending on the results of conditional jumps they need different computing power on otherwise identical sequence of instructions. So they differ distinctly from more deterministic RISC processors and deterministic DSP (Digital Signal Processor), which guarantee exact timing – but have higher system costs.

Thence an exact maximal number of operations for the 95 µs of the PC based Fast Tool Servo controller cannot be specified. Literature assumes average values of 165 MFLOPs (Millions of Floating Point Operations per Second) to 205 MFLOPs per GHz for this type of processor depending on the kind of basic floating point operations [4, 5]. Applied to the Fast Tool Servo System there are approximately 8000 floating point operations available at 650 MHz CPU (Central Processing Unit) frequency and a maximal time for set point generation of 95 µs.

A NURBS surface algorithm of order 2 is in need of about 140 FLOPs for the calculation of a point. That clarifies the scarceness of calculating time available per control cycle. The lacking analytical inversion of the projection of the surface *S(u,v)* to the X-Y-plane from the coordinates *x,y* to the NURBS parameters *u,v* proves to be the critical point.

$$S(u,v)=\begin{bmatrix} S_x(u,v) \\ S_y(u,v) \\ S_z(u,v) \end{bmatrix} \qquad \text{Eq. 1}$$

That inversion can only be done efficiently as Newton approximation [3, 5]. Selecting convenient starting points the Newton algorithm converges super-linear. Nevertheless the numerical complexity is demanding compared to the available calculating time of 95 µs.

Hence, several strategies of NURBS evaluation were implemented to relax the calculating time difficulty with the aid of offline pre-processing. All algorithms have in common the transformation of the polar coordinates of the machine axes *r,c* into the workpiece's cartesian coordinates *X*,*Y*.

The first implemented algorithm (algorithm I) transforms the NURBS into a 2-dimensional matrix Z^* offline. The workpiece coordinate Z is stored depending on the indices *i* and *j*, which in turn are functional linear to the workpiece coordinates *X* and *Y*. The *Z* coordinate's fine interpolation is done online by a Gauss Filter (Eq. 2).

$$Z(x,y)=\frac{\sum_i\sum_j Z^*(i,j)e^{-\left(\frac{(X(i)-x)^2+(Y(j)-y)^2}{k^2}\right)}}{\sum_i\sum_j e^{-\left(\frac{(X(i)-x)^2+(Y(j)-y)^2}{k^2}\right)}} \qquad \text{Eq. 2}$$

The exponential function's numerical performance is poor, depending on the exponent's actual value. An optimized runtime algorithm is capable of calculating a 7x7 matrix leading to satisfying workpiece accuracy.

The second implemented algorithm (algorithm II) works with NURBS (Eq. 3). Since the freeform is given as a cloud of points nothing argues against choosing uniformly increasing knot points of the vectors *U* and *V* as well as choosing appropriate X,Y-coordinates of the control points to obtain a linear and decoupled system of equations in *X* and *Y*.

$$S(u,v)=\begin{bmatrix}k_1 & 0 & 0\\ 0 & k_2 & 0\\ 0 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}u\\ v\\ 0\end{bmatrix}+\begin{bmatrix}x_o\\ y_o\\ S_z(u,v)\end{bmatrix}$$

Eq. 3

The time-consuming inversion of the Newton algorithm to determine *u,v* from *x,y* can be avoided. The calculation of one point takes approximately 150 FLOPs.
Algorithm III can be applied to NURBS without restriction of the parameters. The inversion $S(u,v)=[X_w,Y_w]'$ can be achieved as follows. First the distance vector has to be formed (Eq 4.).

$$r(u,v)=S(u,v)-\begin{bmatrix}X_w\\ Y_w\end{bmatrix}$$

Eq. 4

The scalar product of *r* and the tangent on the NURBS surface *S(u,v)* will be 0, if the distance *r* is minimal (Eq. 5).

$$f(u,v)=r(u,v)\cdot S_u(u,v)=0$$
$$g(u,v)=r(u,v)\cdot S_v(u,v)=0$$

Eq. 5

Both equations are formulated as Taylor approximation (Eq. 6, Eq. 7).

$$\delta_i=\begin{bmatrix}\Delta u\\ \Delta v\end{bmatrix}=\begin{bmatrix}u_{i+1}-u_i\\ v_{i+1}-v_i\end{bmatrix};\quad J_i=\begin{bmatrix}f_u & f_v\\ g_u & g_v\end{bmatrix};\quad \kappa_i=-\begin{bmatrix}f(u_i,v_i)\\ g(u_i,v_i)\end{bmatrix}$$

Eq. 6

$$\delta_i=J_i^{-1}\kappa_i;\begin{bmatrix}u_{i+1}\\ v_{i+1}\end{bmatrix}=\delta_i+\begin{bmatrix}u_i\\ v_i\end{bmatrix}$$

Eq. 7

The Jacobi matrix's computation is complex, requiring the explicit computation of two first order derivations (S_u, S_v) and four second order derivations (S_{uu}, S_{vv}, S_{uv}, S_{vu}). The matrix operations of the 2x2-equation-system appear minor on the other hand. One Newton step requires 600 FLOPs. Depending on good start values for *u,v* the algorithm needs three to seven iterations leading to 1800 to 4200 FLOPs in total.
One typical strategy to avoid the complex computation of the second order derivations is to apply a Quasi Newton Algorithm by approximating the inverse Jacobi matrix from iterative updates with the gradients by the BFGS-formula. This type of matrix update manages with less evaluations, in our case 350 FLOPs. However a linear search is necessary to detect the exact minimum in search direction which needs at least one additional NURBS surface point evaluations taking approximately 140 FLOPs each. Hence, this type of Quasi Newton Algorithm has no distinct advantages compared to the normal Newton Algorithm in this case.

Machining of Free-Form Surfaces

For the manufacturing of the mentioned free-form mirror the manufacturing process fast tool turning is applicable. The following machine parameters are applied by using a ultra precision lathe and a linear motor driven fast tool servo developed by Fraunhofer IPT:

- spindle speed: 200 1/min,
- infeed: 6 µm,
- feed rate: 1.8 mm/min.

The calculated tool path is shown in Fig. 4. The maximum not rotational part of the free form surface is 1.1 mm. The roughness values at this machining parameters are in a range of Ra = 15 to 25 nm. The form deviation measured with the integrated linear scale of the fast tool servo is below than ±0.4 µm.

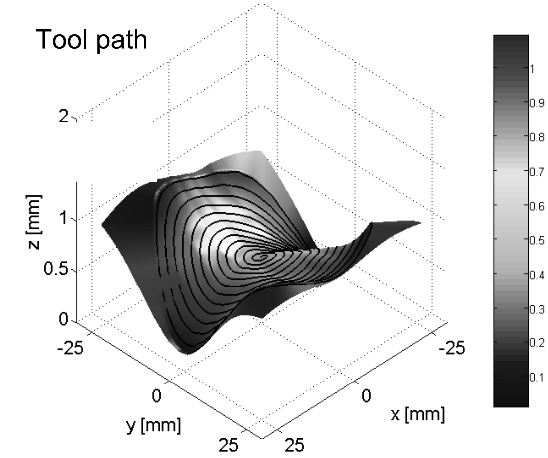

Fig. 4: Tool Path of Free-Form Mirror

The arrangement of the optical components and the illumination function of a mirror with a diameter of 50 mm are displayed in Fig. 5.

In the past the developed ultra precision machining steps are dedicated to specific products and are non-transferable. Therefore, for a flexible, economic and completely automated production with full process control of optical elements with complex geometries the whole process chain involving optical and mechanical design, machining, replication and quality control needs to be considered. Only a combination of flexible trajectory generation, diamond machining, measuring the generated surfaces, detecting the defects, transferring the form deviation to the NURBS data format and recalculating the optical design opens a powerful way for high precision mold making.

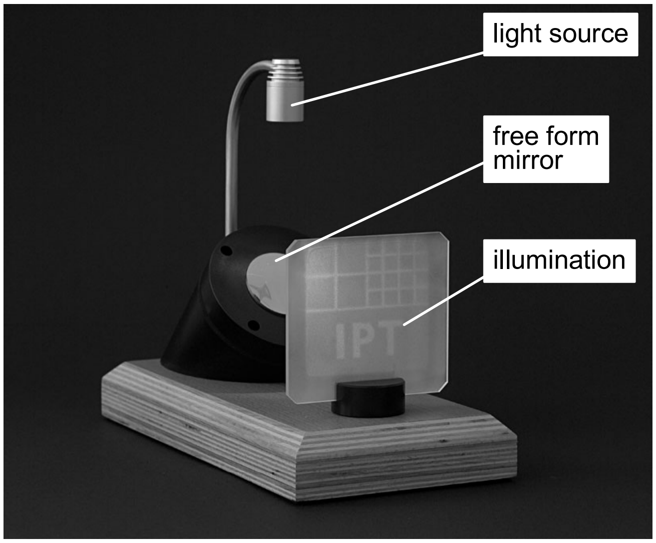

Fig. 5: Illumination function.

Summary and Outlook

In this paper first results of machining molds with free-form surfaces in optical quality using a NURBS based data interface were presented. The main advantage of the implementation data interface into the fabrication process is the flexible and precise calculation of tool paths. As a basic approach we started with the optic design stage for the layout of the targeted geometry. After a short introduction into NURBS the build-up of a Fast Tool Servo System and its control unit was presented. The surface data of the free-form mirror developed in the optic design are directly transferred to the machine and the Fast Tool Servo System. The machining of free-form surfaces is possible using three different algorithms of online tool path computing. In the future the interfaces have to be tested in order to optimize the used data exchange formats. Also a online trajectory generator for multi-axes machining will be developed.

Acknowledgments

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