Recent Advances in Ultraprecision Machining for Freeform Optics

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Contents

- **Freeform optical surfaces**
  - Definitions, Advantages, Mathematical Description, and Engineering Applications;

- **Diamond turning for freeform surfaces**
  - Fast tool servo, Principle for generating freeform surface, Modeling freeform workpiece, Toolpath generation, topography of machined surface;

- **Polishing for freeform surfaces**
  - Bonnet polishing (Zeeko), Magneto-rheological finishing (QED), Belt polishing (Optipro), etc.
How to define freeform optical surface?

- Any non-rotationally symmetric (NRS) or non-axisymmetric optical surfaces (North Carolina State University, Prof. T. Dow, et al, 2005);
- Optical surfaces without rotational symmetry, or that depart or deviate from rotational symmetry (Univ. of Rochester, Prof. J. Rolland, et al, 2012);
- For the freeform surfaces described in $S: z=f(\rho, \theta)$, the shape of $S$ not only depends on the radial variable $\rho$, but also the azimuthal variable $\theta$. 
Geometrical features

- Let \( S(\rho, \theta, z) \) or \( S(x, y, z) \) be a freeform surface, then
  - for the plane with \( z = z_0 \), the generated contour is always a noncircular curve;
  - for the cylindrical surface \( S_2 \) (\( x = \rho \cos \theta, y = \rho \sin \theta, z \)), the space curve \( C \) can be formed by the intersection between the \( S_2 \) and \( S \), which could not be degenerated into a circle.

\[ z = 1.73 \rho^2 \cos 2\theta + \rho^2 \sin 2\theta + 2(3 \rho^2 - 2)\rho \cos \theta \]

An example of freeform optical surface, which is represented by Zernike Polynomial and originally used to design a wavefront corrector by Meinel et al, 1986, in LLNL.
Machining requirements for freeform optical surface?

- Form errors: from submicrons to nanometers;
- Surface roughness: from nanometers to angstroms;
- Surface waviness: nanometers;
- And position errors (linear and angular position).

Titled flat-form results, P-V error: 0.259 μm.

Titled flat-finish results, Ra: 2.711 nm
Benefits of freeform optical surfaces?

- Significantly improve the performance of an optical system, compared with spherical and rotationally symmetric aspheric optical surfaces;
- Dramatically reduce the number of optical elements used in an optical system;
- Enable the optical system to be much more lightweight, and reduce the calibration complexities of optical elements;
- Increase the optician’s design degrees of freedom, and facilitate the performance target driven design of optical system.
Simple examples of freeform optical surfaces

- Off-axis conic surfaces;
- Toroidal surfaces;
- Biconic surfaces;
- $x$-$y$ polynomial surfaces.

Off-axis conic used in Keck Telescope primary mirror

Biconic used in Infrared Multi-Object Spectrometer (IRMOS)
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<td>Keck telescope</td>
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<td>Three-mirror-anastigmatic (TMA) telescopes</td>
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<td>Toroidal surfaces</td>
<td>Ophthalmic optics</td>
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<tr>
<td>Biconic surfaces</td>
<td>Infrared Multi-Object Spectrometer (IRMOS)</td>
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<td>x-y polynomial surfaces</td>
<td>Cubic Phase Plate</td>
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<td>Head-mounted display (HMD)</td>
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</table>

- Mark C. Gerchman. "Description of off-axis conic surfaces for nonaxizymmetric surface generation", Proc. SPIE 1266, In-Process Optical Measurements and Industrial Methods, 262 (August 1, 1990);
Off-axis conic geometry.

(a, b): the center of off-axis segment.

The contours of an off-axis conic surface.
\[
    z = R_b - \sqrt{(R_b - R_c + \sqrt{R_c^2 - r^2 \sin^2 \theta})^2 - r^2 \cos^2 \theta}
\]

**Toroidal surface, S. Ludwick, 1999**

\[
    z = \frac{x^2 / R_x + y^2 / R_y}{1 + \sqrt{1 - (1 + k_x) x^2 / R_x^2 - (1 + k_y) y^2 / R_y^2}}
\]

**Biconic surface, R. Winsor, 2000**

\[
    z_3 = d_1 + d_2 \rho \cos \phi \pm \sqrt{d_3 + d_4 \rho \cos \phi + d_5 \rho^2 + d_6 \rho^2 \cos^2 \phi}
\]

**Off-axis conic surface, M. Gerchman, 1990**

\[
    z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} + A_1 x y^0 + A_2 x^0 y^1 + A_3 x^2 y^0 + A_4 x^1 y^1 \\
    + A_5 x y^2 + \cdots + A_N x^{i-j} y^j
\]

**x-y polynomial surface, Z. Zheng, 2010**
Freeform optical surface representations

- **Orthogonal basis functions**
  - Zernike polynomials, wavelet basis functions, Forbes functions, etc;
- **Radial basis functions (RBF)**
  - Gaussian basis function;
- **Spline basis functions**
  - B-spline surface, NURBS.
Hybrid freeform optical surfaces

- Any freeform surfaces constructed by incorporating a non-rotationally symmetric (NRS) surface into a rotationally symmetric aspheric surface (substrate)
  - e.g., hybrid conic and Zernike or x-y polynomial;
- Any freeform surfaces constructed by incorporating a series of aspheric surfaces into a plane, spherical, or aspheric substrate
  - e.g., lens array, mirror array;
- Any freeform surfaces represented by two NRS surface equations
  - e.g., hybrid RBF and local $\phi$-polynomial surfaces proposed by Univ. of Rochester, 2013.
\[ z = \frac{cr^2}{1 + \sqrt{1-(1+k)c^2r^2}} + \sum_{m,n} \left[ a_{m,n} Z_n^m(\rho, \varphi) + b_{m,n} Z_n^{-m}(\rho, \varphi) \right] \]

\[ Z_n^m(\rho, \varphi) = R_{m,n}(\rho) \cos(m\varphi), \quad Z_n^{-m}(\rho, \varphi) = R_{m,n}(\rho) \sin(m\varphi) , \quad \rho = \frac{r}{r_{\text{max}}} \]

Hybrid conic and Zernike polynomial surface

\( R_{m,n} \): radial polynomials;
\( \rho \): normalized radial coordinate, \( 0 \leq \rho \leq 1 \);
\( c \): vertex curvature;
\( k \): conic constant.
\[
Z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} + \sum_{m,n} w_{m,n} \phi_{m,n}(x, y)
\]

\[
\Phi(\tilde{x}, \tilde{\mu}, \Sigma) = e^{-\frac{1}{2}(\tilde{x} - \tilde{\mu})^T \Sigma^{-1}(\tilde{x} - \tilde{\mu})}
\]

Hybrid conic and RBF surface
   \( \Phi_{m,n} \): radial basis functions;
   \( w_{m,n} \): coefficients;
   \( c \): the vertex curvature;
   \( k \): the conic constant.
## Comparison for freeform surface description

<table>
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<tr>
<th>Examples</th>
<th>Features</th>
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</table>
| **Orthogonal basis function** | • Global approximation;  
• Thousands of terms are required to approximate the local asymmetric features. |
| Zernike polynomials; Forbes polynomials; | |
| **Radial basis function (RBF)** | • Local approximation;  
• Only tens of terms are required to achieve an acceptable accuracy (nanometers). |
| Gaussian function; | |
Fast tool servo (FTS)

• To generate a NRS surface in diamond turning, an oscillatory motion $\Delta x$ or/and $\Delta z$ of diamond tool relative to the machined surface along x or/and z directions is required;
• FTS is an apparatus to enable the diamond tool to oscillate precisely relative to machined surface along x or/and z directions;
• The motion trajectory tracking of a FTS apparatus can be implemented by the closed loop control or the inverse dynamics based open-loop control.
Principle of freeform diamond turning

- A workpiece is clamped on the spindle, rotating by the angle $\theta$ around the axis $z$;
- The $x$-slide translates $x$ forwards along the $x$-direction;
- A FTS apparatus is mounted on the $z$-slide of a turning lathe, and the diamond tool held on the FTS apparatus oscillates $\Delta z$ relative to machined surface;
- The $z$-slide translates $z$ forwards along the $z$-direction, thus the motion of diamond tool is $(z+\Delta z)$;
- With the motion $(x, z+\Delta z, \theta)$ of the diamond tool relative to the machined work, a NRS surface can be created.

1-spindle; 2-machined workpiece; 3-lathe base; 4-tool height adjustment; 5-FTS
Supporting/guiding fast tool servo

- Linear fast tool servo
  - Flexure hinges, air bearing;
- Rotary fast tool servo
  - Blade flexure, magnetic levitation.
Flexure hinges

Flexure hinges used in a linear FTS actuated by VCM, JLU (China), 2013
Blade flexures used in a rotary FTS actuated by Maxwell force, MIT, 2005
Air bearing

Air bearing used in a linear large stroke FTS actuated by linear motor, NCSU, 2005
# Actuating fast tool servo

<table>
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<th>Refs</th>
<th>Strokes</th>
<th>Freq.</th>
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<tbody>
<tr>
<td>Piezoelectric</td>
<td>Piezoelectric actuators</td>
<td>Fraunhofer IPT, Weck, et al, 1995</td>
<td>~100 µm</td>
<td>~1 kHz</td>
</tr>
<tr>
<td>Lorentz force</td>
<td>Linear motor</td>
<td>UNCC, Rakuff, et al, 2009</td>
<td>12 mm</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Voice coil motor</td>
<td>MIT, Ludwick et al, 1999</td>
<td></td>
<td>2 mm</td>
<td>140 Hz</td>
</tr>
<tr>
<td>Brushless rotary</td>
<td>MIT, Montesanti et al, 2004</td>
<td></td>
<td>0.5 kHz</td>
<td></td>
</tr>
<tr>
<td>Maxwell force</td>
<td>Normal-Stress Reluctance Actuator</td>
<td>MIT, Montesanti et al, 2004</td>
<td>5 µm</td>
<td>10 kHz</td>
</tr>
<tr>
<td></td>
<td>Tianjin Univ., Nie et al, 2014</td>
<td></td>
<td>11.3 µm</td>
<td>3 kHz</td>
</tr>
</tbody>
</table>
Basic specifications for fast tool servo

- Maximum stroke
  - Linear FTS (nano, short, medium, and long stroke);
  - Rotary FTS

- Frequency (open-, and closed-loop)
- Frequency bandwidth
- Tracking accuracy
Performance tests for FTS

- **Static stiffness**
  - along the x-, y- and/or z-directions, static loads are respectively exerted on diamond tool tip, and the displacements are measured;

- **Dynamic behaviors (e.g., frequency response)**
  - along the x-, y- and/or, z-directions, dynamic loads (e.g., impulse, sinusoidal, or stochastic excitations) are respectively exerted on diamond tool tip, and the vibration responses of the diamond tool tip are respectively measured;

- **Actuating behaviors (e.g., resolution, frequency response)**
  - Driving electric voltages (e.g., impulse, sinusoidal, swept sine, stochastic excitations) are exerted, the displacements and/or accelerations are measured along the x-, y- and z-directions of the diamond tool.
Configuring fast tool servo

- Motion configuration
  - linear, or rotary

- Degree of freedom (DoF)
  - Single DoF: a translation, or a rotation;
  - Two DoF: two translation (x- and z-axis), or a translation (z-axis) plus a rotation (B-axis)

- Questions
  - Why is a two DoF FTS desired for freeform diamond turning?
  - How to reduce the cross-talk or coupling between the x- and z-directions in a two DoF FTS?
Representing freeform workpiece

- Cylindrical coordinates are generally used to represent the machined workpiece;
- The datum references of workpiece in $x$-, $y$- and $z$-directions should be set as the origin of the workpiece coordinates;
- Desired machined freeform surface should be mathematically represented on the cylindrical coordinate system of workpiece.
Toolpath for FTS based diamond turning

- Establish the mapping between tool location points and tool contact points
  - Reduce to the tangential contact between the tool tip profile and the desired machined surface.

- Determine the toolpath of tool contact points on the desired machined freeform surface
  - **Criteria**: maximum scallop height constrained, constant scallop height, chip load constrained, minimum thickness of cut constrained, optical performance driven, and so on.

- Decompose the obtained toolpath of tool location points;
  - Monotonic tool trajectories \((\rho, \theta, z)\), and oscillatory tool trajectories \((\rho, \theta, \Delta z)\).
Toolpath generated

constant chip load approach

constant radial feed approach

Chip load comparison

constant chip load approach

constant radial feed approach
Machined surface topography for FTS based diamond turning

- Establish the workpiece and diamond tool coordinate system;
- Represent the desired machined surface and the workpiece surface to be cut on the workpiece coordinates;
- Establish the equations describing the diamond tool tip on the workpiece coordinates;
- Determine the coordinates of tool location points on the workpiece coordinates, according to the predetermined toolpath, and measured the errors of motion axes;
- Generate the machined surface according to the intersection, tangential contact, or separation between the diamond tool and machined workpiece.
Machines for FTS based diamond turning

- Moore nanotechnology system, LLC
  - [www.nanotechsys.com](http://www.nanotechsys.com)
- AMETEK Precitech Inc.
  - [www.precitech.com](http://www.precitech.com)
- Cranfields Precision, A Division of Cinetic Landis Ltd.
  - [www.cranfieldprecision.com](http://www.cranfieldprecision.com)
## Commercial single DoF fast tool servo

<table>
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<tr>
<th>Co.</th>
<th>FTS</th>
<th>Specifications</th>
<th>Actuation</th>
</tr>
</thead>
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<tr>
<td>Precitech</td>
<td>Fast tool servo</td>
<td>1000µm@119Hz, 500µm@168Hz</td>
<td>Piezoelectric actuator</td>
</tr>
<tr>
<td></td>
<td>Slow tool servo</td>
<td>10mm@2Hz</td>
<td>Linear motor</td>
</tr>
<tr>
<td>Moore nanotech.</td>
<td>Fast tool servo</td>
<td>6mm</td>
<td>Voice coil motor</td>
</tr>
<tr>
<td></td>
<td>Slow slide servo</td>
<td>≤25mm, 60Hz</td>
<td>Linear motor</td>
</tr>
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</table>
Challenges for freeform diamond turning

- Ultraprecise mathematical description for freeform surfaces, generated toolpath, and decomposed tool trajectories;
- Innovative processing approaches for brittle and ferrous materials to be diamond turned;
- Backlash effects of high frequency fast tool servo against diamond turning machine;
- Static/dynamic coupling between the x- and z-directions in a two DoF fast tool servo;
- Size effect resulted from the variation of chip load during freeform diamond turning;
- Ultraprecise in-process measurement of cutting force components during FTS based diamond turning.
# Conformal polishing for freeform surfaces

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<th>Polishing processes</th>
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<td>University of California</td>
<td>Stressed mirror polishing</td>
<td>Applied Optics, Lubliner and Nelson, 1980</td>
</tr>
<tr>
<td>Zeeko Ltd University college London</td>
<td>Bonnet (inflated membrane) polishing</td>
<td>Proc. SPIE 5180, Walker, 2004</td>
</tr>
<tr>
<td></td>
<td>Non-linear visco-elastic effect based polishing</td>
<td>Optics Express, 18(3), Kim and Burge, 2010</td>
</tr>
</tbody>
</table>
Bonnet Polishing

- Two principal functions – to remove surface and sub-surface damage from a ground part, and then to correct the form.
- A sub-aperture flexible polishing tool is used – an inflated, bulged, rubber membrane of spherical form (‘bonnet’), its rotation axis \( H \) inclined to the local normal of the polished surface.
- The polishing pressure and the contact area can be modulated independently.
Bonnet polishing machine

- A seven-axis CNC polishing machine providing the following the DoFs.
  - H axis: rotation of the bonnet about its axis of symmetry;
  - X, Y, Z axes: positioning of the bonnet with respect to the workpiece;
  - A, B axes: orientation of the bonnet’s axis in the coordinate frame of the machine;
  - C axis: rotation of the workpiece.
Magneto-rheological finishing (MRF)

- A magnetorheological (MR) fluid inside a magnetic field creates a sub-aperture “polishing lap”, the shape and stiffness of which can be magnetically controlled.
- This sub-aperture “polishing lap” conforms to the local surface curvature in such a way that it does not have the problems with tool/part shape mismatch.
- Figure errors: better than λ/50 (P-V); Roughness: less than 1nm.
Ultraform finishing (UFF)

- UFF utilizes a belt of polishing material wrapped around by a compliant wheel that rotate and contact the part to remove material.
- This belt polishing system provides a tuned stiffness that is capable of conforming to the polishing surface.
Notes on freeform polishing

- Have a stable and deterministic tool influence function (TIF) or material removal function;
- Demand highly precise full-aperture metrology for freeform surfaces;
- Avoid zones resulted from the curvature mismatch between the tool and the surface;
- Have a polishing tool that conforms to freeform shapes, and maintains a intrinsic smoothing.
Summary

- Fast tool servo (FTS) based diamond turning is recognized as a promising approach to creating freeform surfaces, it is of the advantages of high efficiency, high precision, and cost-effective, but there exist some issues to be solved, such as generating the freeform shapes of brittle and ferrous materials, developing two degrees of freedom or more than FTS, and so on;

- The existing conformal polishing for freeform surfaces, e.g., bonnet polishing, magneto-rheological finishing, and ultraform finishing is of excellent capability of shape adaptation, but how to balance the compliance and smoothing effect of polishing tool should be further investigated.
Thank you for your attention.