Highlights of Presentations
Part 2 of 3
Day 1, Afternoon
compiled by
Kevin Thompson, PhD
Synopsys, Inc.
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<tr>
<th>Time</th>
<th>Session Title</th>
<th>Presenter and Institution</th>
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<tr>
<td>8:40</td>
<td><strong>Opening Remarks: Is This History in the Making?</strong></td>
<td>Kevin Thompson, Synopsys, Inc., USA</td>
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<tr>
<td>9:00</td>
<td><strong>Freeform Surfaces for Imaging Systems</strong></td>
<td>Norbert Kerwien, Carl Zeiss Corp., Germany</td>
</tr>
<tr>
<td>9:25</td>
<td><strong>Current Techniques for Diamond Machining Freeform Optics</strong></td>
<td>Gregg Davis, II-VI, Inc., USA</td>
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<tr>
<td>9:50</td>
<td><strong>Realizing an Optical System with Phi-Polynomial Freeform Surfaces</strong></td>
<td>Kyle Fuerschbach, University of Rochester, USA</td>
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<tr>
<td>11:00</td>
<td><strong>Specifying Shape...What Could We Hope For and Can It Be Achieved</strong></td>
<td>Gregory Forbes, QED Technologies Inc., Australia</td>
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<td>11:25</td>
<td><strong>Smooth Radial Basis Functions Viewed as a Generalization of Multivariate Polynomials</strong></td>
<td>Gregory Fasshauer, Illinois Institute of Technology, USA</td>
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<td>11:50</td>
<td><strong>Moving from Phi-Polynomial to Multi-centric Radial Basis Functions</strong></td>
<td>Aaron Bauer, University of Rochester, USA</td>
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<tr>
<td>13:15</td>
<td><strong>SMS 3D: A Freeform Optics Design Method</strong></td>
<td>Juan-Carlos Miñano, LPI, Universidad Politecnica de Madrid, Spain</td>
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<tr>
<td>13:40</td>
<td><strong>Geometric Methods of Design of Freeform Surfaces with Prescribed Optical Properties</strong></td>
<td>Vladimir Oliker, Emory University, USA</td>
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<tr>
<td>14:05</td>
<td><strong>A Starting Point Approach for Nonimaging Reflector Design</strong></td>
<td>Cristina Canavesi, University of Rochester, USA</td>
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<tr>
<td>15:10</td>
<td><strong>40 years of Freeform Surfaces</strong></td>
<td>Daniel Bajuk, ZYGO EPO, USA</td>
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<tr>
<td>15:35</td>
<td><strong>Freeform Surfaces Have Aberration Fields Too</strong></td>
<td>Kevin Thompson, Synopsys, Inc., USA</td>
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<tr>
<td>16:00</td>
<td><strong>Two Freeform Mirror Designs with SMS 3D</strong></td>
<td>Lin Wang, Universidad Politecnica de Madrid, Spain</td>
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<td>17:30</td>
<td><strong>BIG BIRD</strong></td>
<td>Phil Pressel, Quartus Engineering Company, USA</td>
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<td>9:00</td>
<td><strong>The Art of Tailoring Freeform Surfaces for Illumination</strong></td>
<td>William Cassarly, Synopsys, Inc., USA</td>
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<td>9:25</td>
<td><strong>Freeform Optics at OSRAM: What We Have, What We Miss, What We Need</strong></td>
<td>Julius Muschaweck, OSRAM GmbH, Germany</td>
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<tr>
<td>9:50</td>
<td><strong>Freeform Optics for a Linear Field of View</strong></td>
<td>Fabian Duer, Vrije Universiteit Brussel, Belgium</td>
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<tr>
<td>11:00</td>
<td><strong>Nonimaging Freeform Optics Applications at LPI</strong></td>
<td>Pablo Benitez, Universidad Politecnica de Madrid, Spain</td>
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<tr>
<td>11:25</td>
<td><strong>F-RXI Photovoltaic Concentrator: A High Performance SMS-3D Freeform Köhler Design</strong></td>
<td>Marina Buljan, Universidad Politecnica de Madrid, Spain</td>
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<tr>
<td>11:35</td>
<td><strong>Augmented Reality Displays a Playground for Freeform Surfaces</strong></td>
<td>Jannick Rolland, University of Rochester, USA</td>
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Day 1
Afternoon Session

Illumination Optics; an Introduction
Bill Cassarly, Synopsys, Inc., USA

13:15 SMS 3D: A Freeform Optics Design Method
Juan-Carlos Miñano, LPI, Universidad Politecnica de Madrid, Spain

13:40 Geometric Methods of Design of Freeform Surfaces with Prescribed Optical Properties
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15:35 Freeform Surfaces Have Aberration Fields Too
Kevin Thompson, Synopsys, Inc., USA

16:00 Two Freeform Mirror Designs with SMS 3D
Lin Wang, Universidad Politecnica de Madrid, Spain
Surfaces for Illumination
Part 1 - Introduction

Freeform Incubator

Dr. Bill Cassarly
Optical Research Associates
williamc@synopsys.com
www.opticalres.com
Illumination Optics

- Includes applications in virtually every industry where light must be controlled. Almost all applications now use LEDs.
Reflector Applications

- Luminaires
- Flashlights
- Street lighting
- Medical illuminators
- Automotive headlights
- Projection displays
- Laser beam shaping

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Diffusers and scatter

- Many illumination products combine an optic that collects light and also spread/homogenizes the beam pattern.
  - Lens arrays, faceted reflectors, diffusers

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Predictable Success
Optimization

- Optimization is the ability to automatically refine the performance of a system based upon a user specified performance criteria
- Three primary aspects of optimization
  - Efficient Optimization Algorithm
  - Smart Model Parameterization
  - Robust Merit Function

User Interface ties these elements together
Surface Parameterization

- Surfaces can be described using Equation:
  - e.g., XYPolynomial, Zernike, Asphere, etc
- Tailoring and SMS:
  - Compute prescribed surface(s) by numerical integration.
    - Often based upon a source to output mapping
    - Surface commonly represented using NURBS
- Equation that best fits NURBS sometimes used
Optimization Variables

• Equation Parameters
  – e.g., radius of curvature, XY polynomial coefficients

• Source to Output Mapping parameters
  – e.g., Width of target, desired Illuminancce
Merit Function

- For many applications, a weighted Merit Function can be used for optimization.
- Weights are used by the designer to help balance tradeoffs.
- Merit functions are often based on ray aiming.
- In illumination, binned Monte Carlo simulation results are often used.

**Basic Equation For Merit Function**

\[
MF = \sum W_g \sum W_i^2 (V_i - T_i)^2
\]

- \(W_g\) = Weight of \(g^{th}\) MF Group
- \(W_i\) = Weight of \(i^{th}\) MF item in Group \(g\)
- \(V_i\) = Current Value of \(i^{th}\) MF item
- \(T_i\) = Target of \(i^{th}\) MF item
Computer Speed makes Monte Carlo Optimization feasible

Ray trace speed ($/RS/s)

Illumination vs. imaging systems
Calculations / ray $> \times 10$
Number of rays $> \times 10^3$
Number of variables $> \times 10$

Early attempts at optical design with computers by James G. Baker
Commercial optical system design software
Computer-aided optimization of optical systems
Commercial illumination (non-sequential) design software
Optimization integrated into illumination design software

SMS 3D: A Freeform Optics Design Method

J.C. Miñano$^{1,2}$, Pablo Benítez$^{1,2}$

$^1$Universidad Politécnica de Madrid, Spain
$^2$LPI, USA
Design methods in nonimaging optics

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<table>
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<tbody>
<tr>
<td>1.</td>
<td>String method (1960’s)</td>
</tr>
<tr>
<td>2.</td>
<td>Flow line method (1970’s)</td>
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<tr>
<td>3.</td>
<td>Taylored Edge-ray method (1980’s)</td>
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<td>4.</td>
<td>Poisson bracket method (1980’s)</td>
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<td>5.</td>
<td>Lorentz geometry method (1990’s)</td>
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<td>6.</td>
<td>Point-source Differential Equation methods (1960’s)</td>
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<tr>
<td>7.</td>
<td>Numerical optimization methods (1990’s)</td>
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<tr>
<td>8.</td>
<td>Simultaneous Multiple Surface (SMS) method (1990’s)</td>
</tr>
</tbody>
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2D = rotational or linear symmetry
3D = freeform
SMS design method

SMS 2D
NonImaging
• 2 aspherics
• Highly developed

SMS 3D
Imaging
NonImaging
• 2 freeform surfaces
• SSL and CPV applications

• Up to 4 aspherics
• Non-paraxial, high-order surfaces
• Object and pupil discretization

• 2 freeform surfaces for asymmetric imaging
• Object discretization

Freeform Optics Incubator Meeting
Washington, October 31, 2011
RXI collimator

Free form RXI
Conclusions

• SMS 3D is a free-form optical design method. As yet up to 2 surfaces/device have been designed. Following the same scheme as in SMS 2D, four or more free-form surfaces may be handled with this method.

• As a nonimaging design tool:
  – it allows control of the size and rotation of the pinhole images of the source, which is critical for extended sources.
  – Efficiency – tolerance improvement.
  – Reflector combinations avoiding blockage
  – Compact designs

• As an imaging design tool:
  – Field contours can be better adapted to rectangles: Less optical surfaces
  – reflector combinations avoiding blockage
  – Compact designs
Geometric methods for design of freeform surfaces

Vladimir Oliker
Emory University, Atlanta
oliker@mathcs.emory.edu

Freeform Optics Incubator Meeting
Washington, DC
30 October – 1 November, 2011
Two basic approaches to design of freeform optics (See J. C. Miñano, P. Benítez, A. Santamaría, Opt. Review, 2009):

- **Numerical Optimization** of some Merit function(s). Numerous procedures exist; The design is usually a local optimum of the merit function

- **Direct methods:** require a correspondence (map) between prescribed input and output fronts
  
  - (a) Spherical wave fronts were considered already by R. Descartes;

  - (b) The SMS method, J. C. Miñano, P. Benítez et al.;

  - (c) Geometric methods (≡The Monge-Ampère equations), V.I. Oliker et al.
Philosophy of applying geometric methods to design of freeform mirrors/lenses:

1. Recognize special surfaces (i.e. quadric(s), Cartesian ovals,...) suitable for the problem (these usually solve the problem if one of the given intensities replaced by a sum of Dirac masses)

2. Describe the freeform mirrors/lenses as expressions for lower and upper envelopes of such special surfaces (This also defines convex/non-convex solutions, the admissible functions and often a very useful Fermat-like functional!)
Philosophy of applying geometry to design of freeform mirror/lenses (cont-d):

3. (a) An iterative method based on a monotone variation of parameters defining special surfaces has been developed by V. Oliker et al.; This method is very general and intuitive and the procedure is guaranteed to converge to the true solution (a priori chosen by the user; may become slow when the number of special surfaces is large.

3. (b) A new method was developed by V. Oliker et al. in recent years. It is based on specific rules for formulating a problem-dependent physically motivated Fermat-like functional to be optimized; the numerical scheme is guaranteed to converge to the true solution (a priori chosen by the user); it allows determination of tens of thousands of data points on each mirror/lens.
**Test design 1. A freeform mirror.** The mirror below transforms an intensity from a point source into a prescribed far-field distribution; the mirror was designed by V. Oliker; data for the design was supplied by J. C. Miñano, P. Benítez;
Our main claims are:

- Freeform lenses can be designed under very general assumptions.

- Analytically, these problems can be formulated as:
  (a) PDE’s of Monge-Ampère type, (b) Variational problems

- Two designs are available for the same data; one of them always consists of a concave and convex lenses.

- Practical computational approaches are developed for calculating solutions with \( \approx 40,000 \) surface data points on each lens.
A starting point approach for non-imaging reflector design

Cristina Canavesi,¹ William J. Cassarly, PhD,² and Prof. Jannick P. Rolland¹

¹The Institute of Optics, University of Rochester
²Synopsys

OSA Freeform Optics Incubator Meeting
30 October – 1 November, 2011
Some Reflector Design Methods

Numerical integration

- Set up system of equations and solve numerically


Variable separation mapping

- Subdivide problem in equi-flux regions and assign mapping.
For unfaceted reflectors, can result in issues at the boundary.

Some Reflector Design Methods

Oliker supporting ellipsoids algorithm

• Initially flux is all collected by one ellipsoid, then the ellipsoids are scaled iteratively to all receive rays


Linear programming (Oliker/Wang)

• Variational formulation

3D Example and Comparison with Supporting Ellipsoids Starting Point

Starting point from ellipsoid algorithm

Starting point from linear program

Source ± 45°
Target ± 6°

Optimized solution for point source

Flux

Ellipsoid #

- ellipsoid algorithm
- linear program

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Conclusion

- The linear program finds a solution in which the rays represent intersections between paraboloids.
- Running the linear programming method with a small or big number of rays per reflector yields the same focal parameters.
- With a low number of rays per reflector, the linear programming starting point is better than the ellipsoids starting point (lower rms, lower peak-to-valley).
40+ Years of Freeform Surfaces

Dan Bajuk
dbajuk@zygo.com
Bob Kestner
bkestner@zygo.com

ZYGO
Extreme Precision Optics
Richmond, CA

November 1, 2011
Freeform Surface Definition

“Freeform Optical surfaces are defined as any non-rotationally symmetric surface or a symmetric surface that is rotated about any axis that is not its axis of symmetry.”

- Design tools for freeform optics – Authors: K. Garrard; T. Bruegge; J. Hoffman; T. Dow; A. Sohn

- Surface examples
  - Bi-cubic spline
  - Bi-variant polynomial
  - Aspheric cylinder
  - Toroid
  - Phase correctors
  - Zernike surfaces
  - Off-axis asphere
    - fabricated via freeform methods
TV Phosphor Exposure Lenses

- TV lenses freeform aspheres were used to lithographically place phosphors on a color CRT tube face in the position where the electron beam (R,G,B) would land during use.
- Lenses were generally produced in small lots (6 to 12) for each color tube design
- TV lenses were manufactured at rates up to 40/week between 1967 and 2003

Typical TV lens profile – aspheric departure about 4mm

Hartmann test used to verify surface profile
Alvarez Lens Mold

- Manufactured for an automated vision analyzer
  - Cubic form of Alvarez lens produces variable power by translating two lenses rotated by 180°
Hubble Space Telescope Optics

Space Telescope Imaging Spectrograph (STIS) Corrector

COSTAR
NICMOS
GHRS
COS

WFPC 2
STIS
ACS

Spherical test interferogram showing anamorphic shape

TEST RESULTS OF TEST #3 FINAL CGH TEST POST-GEOMETRY

2.7nm rms

INTERFEROGRAMS
Full surface aperture shown at best focus

Deep Field ACS image
EUV Mirrors

- Zygo EPO has been supplying EUV optics to the semiconductor community since 1992
- Continued process improvement has resulted in 0.1nm rms results over a broad spatial spectrum from full aperture to 10nm

<table>
<thead>
<tr>
<th></th>
<th>Figure</th>
<th>MSFR*</th>
<th>HSFR*</th>
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<tbody>
<tr>
<td>Specification</td>
<td>&lt;0.10nm rms</td>
<td>0.14nm rms</td>
<td>0.15nm rms</td>
</tr>
<tr>
<td>Results range</td>
<td>0.087–0.051</td>
<td>0.121–0.089</td>
<td>0.079–0.055</td>
</tr>
</tbody>
</table>
Lithographic Freeform Fold Mirror

Total sagitta 37.8μm PV

Freeform component 3.6μm PV

Optical & CMM metrology comparison

Optical test

CMM measure alone well characterizes the freeform surface

CMM test artificial fringes

0.25λ (158nm) PV requirement

Test at completion 11.8nm RMS 82nm PV

3 position stitching test using a software null
Summary

- Freeform surfaces have been manufactured for over 40 years using computer controlled fabrication methods
  - Today’s processes can achieve nanometer precision

- Flexible and precise figure metrology methods are key
  - CGH interferometry
  - Stitching interferometry
  - Coordinate measuring machines
  - Metrology covering a broad spatial frequency range is required for the most demanding application
  - PSD evaluation
Freeform Surfaces have Field Dependence Too

Kevin P. Thompson, PhD

Group Director, R&D/Optics, Synopsys, Inc.
Visiting Scientist, Institute of Optics, UofR

October, 2011
Two flavors of Freeform surfaces

- Freeform Surfaces for Optical Design
  - Comatic and/or Phi-Polynomial (Zernikes)

- Multi-centric Radial Basis Functions
These are THE Aberrations (there are not any others)

Z9: Spherical

Z7/8: Coma

Z5/6: Astigmatism

Z10/11: Elliptical Coma (Trefoil)

Fringe
This is Important
(generalizing for no symmetry)

A fundamental assumption has been that the “Y-axis” is aligned to the field point of interest – this has been a long standing impediment

Zernike Polynomials

Nodal Aberration Theory
Freeform surfaces reveal the true nature of astigmatism

3rd Order Aberrations with Freeform

3rd Spherical

3rd Coma

3rd Astigmatism
Conclusions: Impact of “Freeform Surfaces” on Optical Design

• The addition of comatic surfaces to the suite is a dramatic advance for optical design

• The new design space is virtually unexplored and for unobscured mirror systems and intrinsically nonsymmetric designs (e.g. Head Worn Displays) the new opportunities are substantial

• Testing is the dominant impediment at this time
Two Freeform Mirror Designs with SMS 3D

Wang Lin, Pablo Benítez, J.C. Miñano, Guillermo Biot

Universidad Politécnica de Madrid
**Design description**

<table>
<thead>
<tr>
<th>Object (16:9)</th>
<th>Image (16:9)</th>
<th>F#</th>
<th>Magnification</th>
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<tr>
<td>13.3 X 7.5mm</td>
<td>6.65 X 3.725mm</td>
<td>2.5</td>
<td>0.5</td>
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**Design parameters**

<table>
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<tr>
<th>Parameter</th>
<th>Constraint</th>
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</thead>
<tbody>
<tr>
<td>$P_{obj}$ ( $R_0$, $\theta_0$, $\theta_n$)</td>
<td>Free</td>
</tr>
<tr>
<td>$P_1$ ( $R_1$, $\theta_1$)</td>
<td>Free</td>
</tr>
<tr>
<td>$P_2$ ( $R_2$, $\theta_2$)</td>
<td>Fixed</td>
</tr>
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</table>

OSA Freeform Optics Incubator Meeting  
Washington, 31 October 2011
One of two examples presented for configuration 1

1st configuration

++ RMS_Avg = 6um
Distortion < 0.2%

Front view

Perspective view

OSA Freeform Optics Incubator Meeting
Washington, 31 October 2011
One of four examples presented for configuration 2

2\textsuperscript{nd} configuration

++ RMS\_Avg = 5um  
Distortion < 0.6%

+- RMS\_Avg = 30um  
Distortion < 0.5%

RMS (mm) SMS3D Design

Distortion (mm) SMS3D Design

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Summary

- Optimization with SMS 3D method
- Exploration of 4 families of 2 configurations