Freeform Optical Surfaces

Report from OSA's First Incubator Meeting

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Just as business incubator programs are designed to support the development of fledgling companies, OSA's new incubator meeting series is structured to encourage the growth of exciting new areas within optics. The first one was devoted to the topic of freeform optics—an area that is actively evolving due to recent technological advances.

In the June 2012 issue of *Optics & Photonics News*, we described a revolution that is under way in a 130-year-old area of optical design: freeform optical surfaces. For the first time, technology development is moving away from rotational symmetry with the introduction of φ-polynomial surfaces.

In light of this, researchers and industry professionals must work together as never before to understand the implications of the resulting shifts in the field. OSA provided a key forum to do that with their new incubator meeting format, which was initiated in late 2011 with a gathering around this very topic.

Our previous article described the evolution of surface shapes in optics from the 1600s through the present day. It also summarized the general classes of surface shapes, including spheres, conics, aspheres, XY polynomials, φ-polynomials and multicentric radial basis functions (RBFs). This article will cover the material presented at the incubator meeting, which intertwined themes relevant to both the imaging and non-imaging (illumination) communities.

Five disciplines were represented at the meeting. They included: fundamental mathematicians, mostly working in non-imaging; optical designers and instrument developers from both the imaging and non-imaging sides; optical fabricators ranging from IR diamond turning (II-VI) to EUV lithography (ZYGO Extreme Optics, Zeiss); the optical testing community; and the end user community (e.g., OSRAM). At the opening, the needs of these disciplines and communities seemed very different, but common themes emerged over the course of the meeting.

The industry shift

The shift in the industry toward φ-polynomial surface shapes was initiated by perfecting five-axis diamond-turning and the simultaneous evolution of computer-controlled small-lap polishing, which occurred around 2004. So now the design community is in the unique position of having an advanced fabrication capability without the infrastructure to leverage it. The designers still need an aberration theory for these surfaces that can be used for design, a community-wide standard surface shape description, and a robust capability for testing these surfaces.

As the φ-polynomial surface shape rapidly matures within industry, the research community is simultaneously looking forward to the next generation. Potentially, the final horizon in the context of macro-scale optics is multicentric, multiscale basis functions—a concept that was introduced by Cakmakci and Rolland in 2008.

(Above) Attendees at OSA's incubator meeting on freeform optics.

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It is difficult to convey how significant this transition is within the imaging community. It is a true revolution. The reason is simple: Until the fabrication of these surfaces became feasible, there was no independent control of the three Seidel aberrations—spherical, coma and astigmatism—that fundamentally limit the field of view and the f/number coverage that can be achieved with any particular optical form. This is manifested by the fact that the amount of coma and astigmatism in a design was directly related to the level of spherical aberration introduced at a surface.

These are explicitly linked parametric dependencies, and they cannot be independently controlled until the φ-polynomial class of surfaces emerge. They create pathways to an entirely new, unexplored and expansive optical design space. We would speculate that this may be for optical systems as transformative as the emergence of the Google search engine was to the Internet.

When everything changes, nearly all of the expectations and assumptions must be revised. Somewhat surprisingly, one thing that does not change is the fundamental aberration forms. There are no "new" aberration types when φ-polynomial surfaces are introduced. What becomes more complex are the field dependencies of the long studied rotationally symmetric manifestations of these aberrations (low and higher order spherical aberration, coma and astigmatism).

Overview of freeform surfaces in non-imaging systems

For non-imaging/illumination systems, the use and development of freeform surfaces is much more advanced due to the lower surface quality required and the earlier availability of design methods. In the 1990s, a number of companies began to develop computer-simulation environments that enabled the efficient and accurate simulation that replaced multiple generation prototypes. This was accompanied by the introduction of optimization to complement—and sometimes substitute for—the existing analytical methods, which some time later became available in commercial software that was first introduced in LightTools in January 2004.

This transition was predictable. The industry was relying on multiple cycle prototypes until raw computer speed finally enabled simulation. The figure on the facing page shows an interesting perspective on computer speed as applied to this industry. In the automotive industry, the introduction of non-imaging/illumination optics simulation on a commercial scale revolutionized the market due to its impact on headlight design. How is that?

It's because suddenly automotive engineers did not have to design cars around large, circular lights covered by a dome. Instead, they could insist that the headlight adapt to the shape of the car—which of course they did. Conformal headlights became the norm by 2000. There was no turning back after that. In fact, when simulation was first introduced, the design of the headlight dominated the time to market for any new car body!

In non-imaging optical design at present, spline-based modeling is often the basis function for the surface shape, particularly non-uniform rational splines

What is an incubator meeting?

Incubators are a new OSA meeting format. They are small gatherings that are well suited to topics that involve highly multidisciplinary subjects and emerging fields of optical engineering or optical science. This series is designed to provide dynamic discussion around a topical area that encompasses—in part or in whole—a subfield that has not yet matured to the level of a topical meeting or even a session track at a large meeting such as the Conference on Lasers and Electro-Optics or Frontiers in Optics.

To make these meetings easy to organize quickly, OSA has integrated its facilities in Washington, D.C., with a local boutique hotel to provide an on-demand plug-and-play format.

As a goal, OSA aims to have the incubators represent attendees and contributors from all over the world who are part of a cross-section of multiple, interdependent communities, including academia, industry and government agencies. The ideal group size is 50-60, but it can range from 25-75.

OSA board member Jannick Rolland, one of the coauthors of this article, is helping to organize and coordinate this exploratory new type of meeting. If you are interested in the possibility of having an incubator in an area related to your specialty, please contact OSA staff member Marcia Lesky for more information; her email is mlesky@osa.org.

Attendees at OSA's incubator meeting on freeform optics.

Attendee distribution for the first OSA incubator on freeform optics

Attendees	Non-imaging	Imaging	Both	Other	Total
Mathematicians/software	5	1	3	-	9
Designers/instrument devel.	10	11	6	-	27
Fabricators	1	1	5	-	7
Alignment/test	-	3	-	-	3
End users	1	3	1	3	8
Academics	4	1	2	3	10
Industry	8	12	9	1	30
Government	-	3	3	-	6
Students	5	3	-	-	8
International	11	2	2	-	17
Women in science	2	1	1	-	4

A total of 54 people represented several countries, including the United States (37), Canada (1), Spain (6), Germany (8), China (1) and Australia (1).

For illumination systems, the use and development of freeform surfaces is much more advanced due to the lower surface quality required and the earlier availability of design methods.

(or NURBS), which is a standard format in the field of computer-aided design. This representation provides local control of the surface for non-imaging/illumination optimization and is also adequate to fit the surface data calculated with methods that provide points and normal vectors to the surfaces, such as the simultaneous multiple surface (SMS) method and the differential equation methods.

In addition, NURBS are becoming widely accepted by non-imaging optics manufacturers. Spline-based representation has not been successfully applied to imaging optimization yet, since the spline surface type presents a daunting optimization problem due to the number of raw parameters that are not directly physically interpretable by the designer.

Company experience and RBF optimization

The meeting opened with an overview by Norbert Kerwien from a company that has represented the state of the art in optics for over a century—Zeiss. His presentation reminded us that the first significant application of a true freeform optical surface was progressive lens forms in eyeglasses. This is a technology that first appeared in 1954. It was commercialized in the 1960s, and became ubiquitous in the 1990s. It is based in XY-polynomial surface shapes and is a major product line for Zeiss. In fact, a number of ophthalmic innovations at Zeiss are based in freeform surfaces. Zeiss was an excellent representative of the community for this forum as they are a fully vertically integrated company when it comes to all aspects of optical design, fabrication, assembly and test, and dissemination of optical systems.

This opening overview was followed by a perspective on the current status of the fabrication of φ-polynomial surfaces presented by Gregg Davis of II-VI, the largest diamond turning facility in the United States. II-VI is one of a handful of companies that has completely implemented this new generation of φ-polynomial surfaces. However, like all facilities, they are searching for methods to test them.

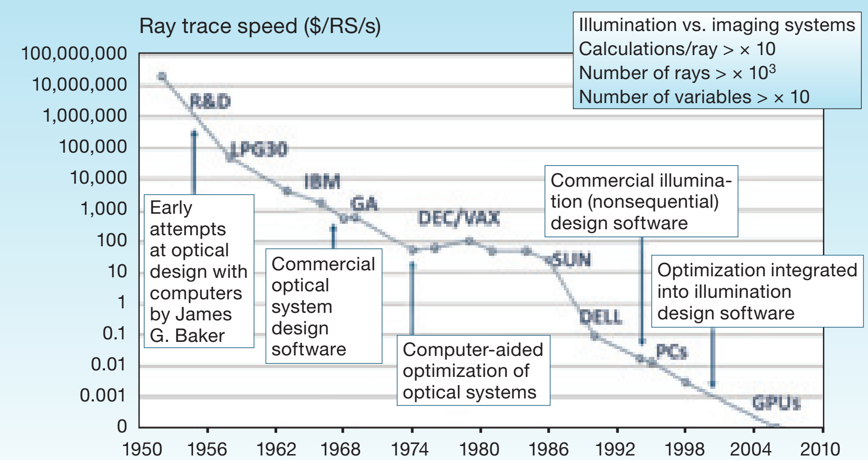
This presentation was followed immediately by a short talk by a graduate student—Kyle Fuerschbach—on the status of the prototype optical system that he designed using φ-polynomial surfaces and nodal aberration theory. The components are in the process of being fabricated and tested at the University of Rochester, and the system is on its way to becoming a fully enabled φ-polynomial surface-based functional optical system.

With a perspective established on the past and current state of technology, the second session of the incubator focused on fostering discussion about which additional surface types are needed to move forward. Greg Forbes of QED, whose work solved the dilemma of how to solve power-series-based implementation for rotationally symmetric aspheres (which dated back to Abbe in 1899), recently released a similar implementation in two dimensions.

His work solves a problem—that conventional polynomial coefficients do not provide information for manufacturing and may be inadequate for numerical computation. It enables testing information to be acquired from surfaces with high slopes that limit what designers can fabricate with certainty, and it has proven to be also very efficient for optimization. Conceptually then, Forbes is working on a slope-conscious version of the Zernike polynomial, orthogonalizing with respect to the mean square gradient of the surfaces.

The next talk was presented by a pure mathematician—Greg Fasshauer of the Illinois Institute of Technology—on the mathematics of RBFs. He gave us a first look at what could be the final generation of optical surface shapes.

[Computer speed makes Monte Carlo optimization feasible]



The history of ray trace speed, enabling simulation in illumination system development.

Adapted from K. Thompson, "Optical Design, Information and Insights," Invited, Presented to the Committee on Optical Science and Engineering, National Academy of Sciences (1996).

Next, Aaron Bauer, a graduate student in Jannick Rolland's group at The Institute of Optics at the University of Rochester, presented results demonstrating the integration of a multicentric RBF surface departure model into a full-complexity optical system model and experimenting with initial approaches to optimization, following in the path of the earlier work of Cakmakci and Rolland.

SMS, high-performance illumination and fabrication

Following a lunch filled with lively discussion in small groups, the meeting's focus shifted to non-imaging optics design. Prof. Minano of the Universidad Politécnica de Madrid & LPI, a leading figure in the field, gave an opening perspective. His group has developed the new design method, SMS, which has revolutionized the field of non-imaging systems.

Minano's group has had many dramatic results in solid-state lighting and concentrating photovoltaics. However, their most visually surprising work was done some years back on a commercial projector for conference rooms. They developed a reflective attachment that allows the projector to be placed some 18 in. from a full-size screen. This was a seemingly unachievable accomplishment that demonstrated that freeform optics will change the world.

Next, Vladmir Oliker of Emory University presented pioneering work based on partial differential equation methods that can lead to high-performance illumination for small-source systems. His talk was followed by a related graduate student talk by Cristina Canavesi, who described her work to develop point-source designs that can be applied to extended sources based on linear programming methods. This led to a long and lively discussion that eventually fragmented into subgroups with localized overlaps of interest on illumination system optimization.

The last session of the first day opened with Dan Bajuk's overview of 80 years of fabrication of true freeform surfaces at Tinsley, which recently became a division of ZYGO. Chris Koliopoulos, the CEO of ZYGO—a publically traded company worth more than $100 million—was an active participant in all of the sessions of the meeting.

Tinsley has a long history of freeform surface fabrication as an early adopter of small-lap, computer-controlled polishing. Its accomplishments are many, but perhaps the most significant was the fabrication of the mirrors that brought the Hubble Space Telescope up to the full intended performance using truly freeform surfaces with shape representative interferograms (pre-null).

NAT and imaging design with mirrors

After this important overview, Kevin Thompson, the imaging lead for the conference, introduced the diverse audience to the current status of non-symmetric imaging optical design tools based on concepts of nodal aberration theory (NAT). As an important historical note, until just a few months ago, NAT was developed in the context of components of otherwise rotationally symmetric surfaces—except for one special case discovered by Schmid of the theory of an astigmatic surface at the aperture stop, which is very relevant to the new generation of thin, active primary mirrors being deployed for astronomy by the European community.

Now, Fuerschbach, in collaboration with Rolland and Thompson, have found that NAT can in fact be extended directly to include freeform surfaces of a φ-polynomial, thereby developing a path forward toward devising a complete theory of the aberrations. This theory confirms the premise of NAT: There are no new aberration types; there are simply more interesting (i.e., complex) field dependencies.

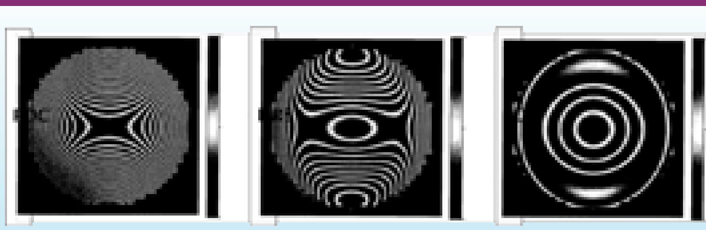
Wang Lin, a student at the Univ. Politécnica de Madrid, gave an early report with Pablo Benítez and Juan Carlos Miñano on imaging design using two freeform mirrors designed by the SMS method, which was done in combination with the optimization of the few free remaining parameters. Their work provides a new perspective on imaging system optimization that was recently explored for rotational SMS aspheres.

State-of-the-art non-imaging design

The second day of the incubator meeting began with a session on the state-of-the art in non-imaging system design, analysis and implementation. In the first talk, Bill Cassarly of Synopsys summarized the state-of-the-design environment for working illumination optics designers, highlighting the optimization of illumination systems. Here, we learned that, when it comes to optimization, the non-imaging community is continuing to follow the path established by their colleagues from the imaging world. However, while tremendous progress has been made, there are still more than a few fundamental breakthroughs needed to reach the same plateau that the imaging community has achieved.

In non-imaging/illumination design, the starting point is still very important, and significant challenges remain in parameterizing the surfaces for optimization. Starting at about 2002,

[The COSTAR anamorphic aspheres]



The surface shapes that resulted in the operational recovery of the optical wavefront for the science instruments on the Hubble Space Telescope. The aspheres are uncompensated and at the center of curvature.

Thompson IODC 1994

When it comes to optimization, the non-imaging community is continuing to follow the path established by their colleagues from the imaging world.

optimization in the imaging community had reached the point where, for more than 95 percent of the problems, the computer was the most effective resource (versus the designer).

The second talk provided an excellent perspective from the viewpoint of an end user. Julius Muschaweck of OSRAM talked about the areas where the optimization and simulation environment is falling short of the needs and visions of the industry that is advancing state-of-the-art products. In the talk, he provided illustrations of some of the advanced surfaces and applications that have been developed with the state-of-the-art design environment, along with a focus view of the factors that may have been holding up progress. He also made some suggestions on how to proceed. In a student presentation, Fabian Duerr of Vrije Universiteit Brussel presented his research on laterally moving SMS freeform lenses for one-axis solar tracking in photovoltaics. He provided a glimpse into his latest work on an impressive analytic SMS solution of two freeform surfaces that can produce stigmatic imaging of three object points in three dimensions.

The final session opened with a presentation by the non-imaging lead for the conference—Pablo Benítez of the University Politecnia de Madrid & LPI. He provided a vision of the current state of both theoretical tools and products that use freeforms developed at LPI. These included automotive LED headlights, color-mixing collimators at the etendue limit and high-performance photovoltaic concentrators with Kölher integration. This was followed by a student presentation, in which Marina Buljan presented her current research on a novel freeform photovoltaic concentrator (named F-RXI), which is being designed and prototyped for its application to a potentially 50-percent-efficient high-concentration four-junction system (using a band-pass multilayer filter and two solar cells).

The last talk provided a glimpse into what the near-term future may hold if the final class of freeform surfaces—the multicentric radial basis functions—succeed. Jannick Rolland, one of the leads for the conference, made this presentation on the past, present and future of head worn displays (HWDs). Her work on fully see-through HWDs points to an exciting future for this technology and possibly the next frontier in mobile devices: getting our hands back!

Postscript

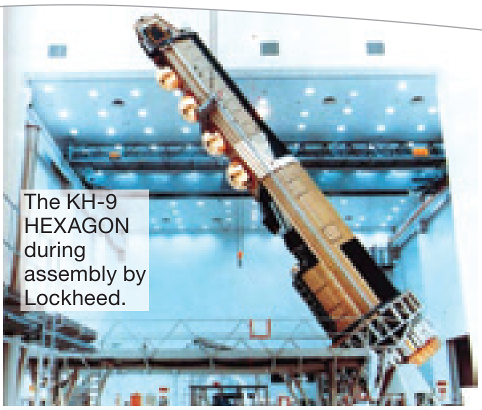
Since the meeting ended, Rolland and Thompson have worked with Fuerschbach on a finding that may be a breakthrough in the aberration of freeform surfaces in the context of NAT; publication in *Optics Express* is imminent. Similarly, Forbes recently proposed a surface description based on a novel set of orthogonal polynomials similar to Zernike φ-polynomials in *Optics Express*.

Like his earlier critical work to replace the power series asphere, this research provides a robust representation that facilitates manufacturability and the ability to reduce the slope of the surface during optimization. This will help engineers to bring the surface within the range of newly developed optical test methods, such as those recently introduced at QED and ZYGO based on different, but effective, strategies.

One of many positive outcomes of the meeting is that it prompted us to apply to the National Science Foundation to fund a Center for Freeform Optics (CeFO), which would be led by The Institute of Optics at the University of Rochester, in partnership with the University of North Carolina at Charlotte and Penn State University.

Clearly, the freeform optic revolution is sweeping the industry—and the first OSA incubator meeting has helped many of the key players to embrace the coming wave.

ONLINE EXTRA: Visit www.osa-opn.org for a complete list of references for this article.


The KH-9 HEXAGON during assembly by Lockheed.

Wikimedia Commons

Big Bird Unveiled

At OSA's incubator meeting on freeform optics, the evening session was a particular treat. It featured a talk by Phil Pressel of Perkin Elmer, who spoke about the most significant surveillance asset ever deployed by the United States—KH-9 HEXAGON, also known as Big Bird.

The Cold-War–era spy satellite was only recently declassified—in September of 2011. As large as a school bus, it carried 60 miles of high-resolution photographic film for space surveillance missions. The main camera system was designed to take stereo images that drew from cameras at both forward and rear locations on the satellite. The system's aperture was defined by an aspheric corrector plate.

Big Bird is a fascinating project. It demonstrates that what is possible can go well beyond what one can imagine when funding is not a boundary.

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