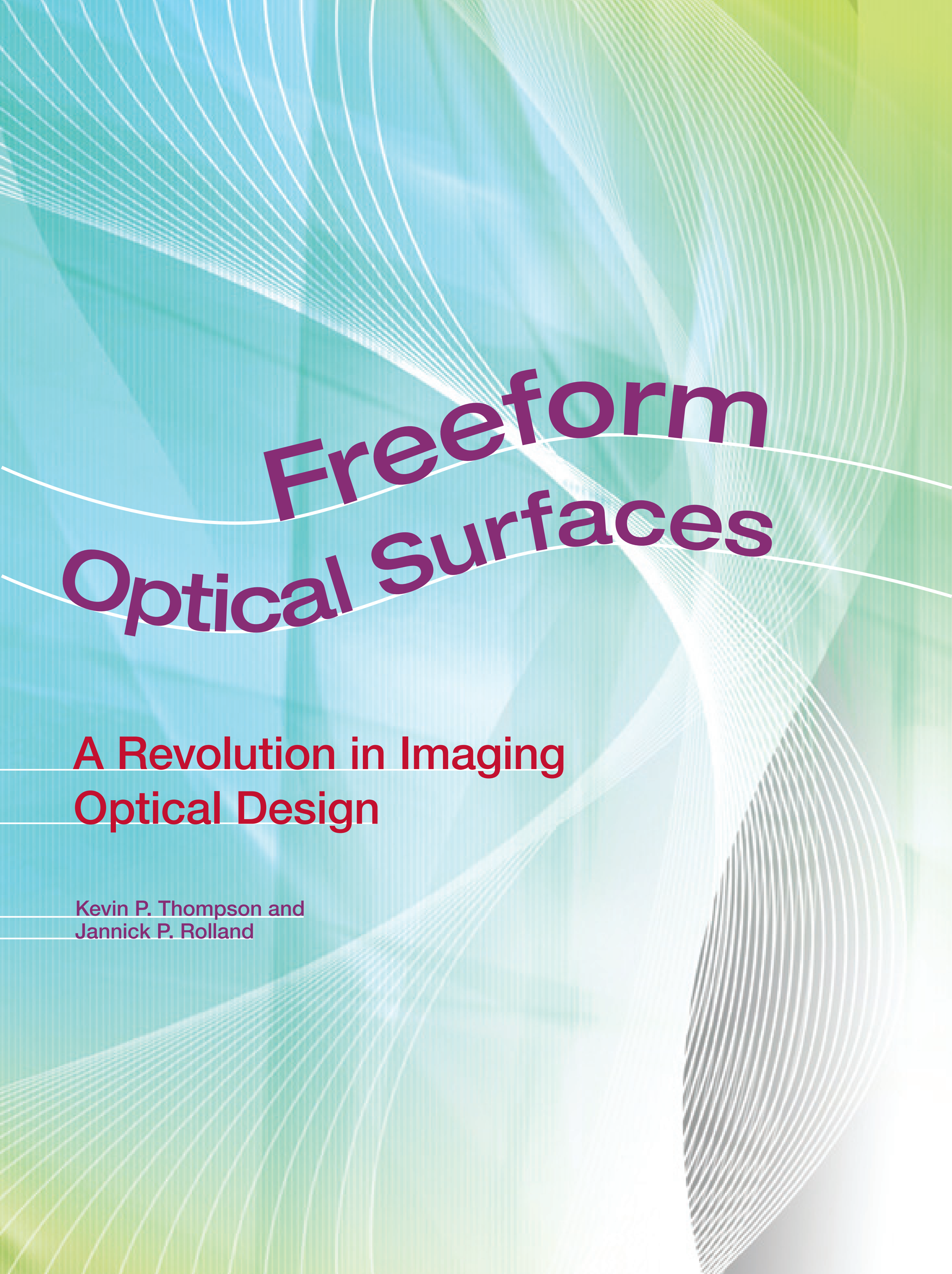
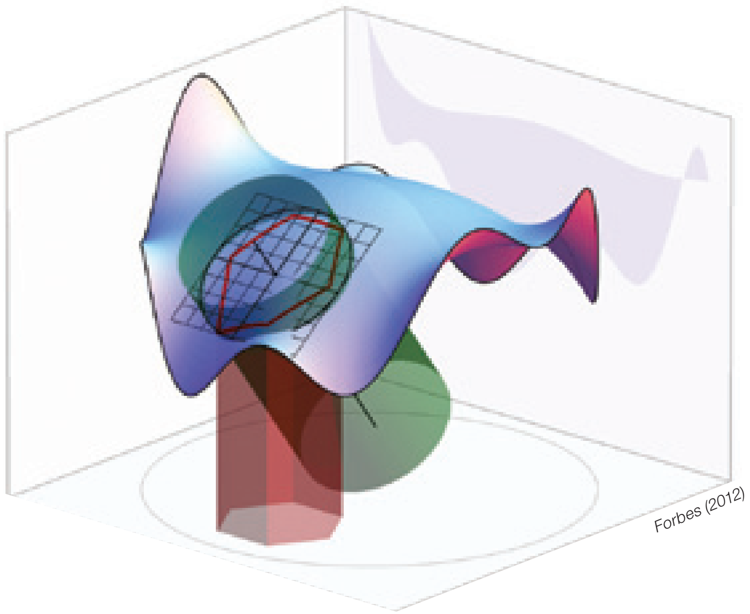


Freeform Optical Surfaces

A Revolution in Imaging Optical Design

Kevin P. Thompson and
Jannick P. Rolland



Forbes (2012)

> A revolutionary optical surface for imaging optical design is the result of developments in the theory of aberrations, techniques in optical system optimization, computation speed, precision fabrication of surfaces without symmetry, and extensions to the range of the surface slopes allowed in optical testing.

In today's world, it is often difficult to separate hype from reality, even in science, particularly when one uses a word such as "revolution." Here, this word is chosen from the perspective of a technology that is 130 years old: the freeform optical surface. While astronomers and a few mathematicians had developed some perspectives on mirror shapes and simple lens systems extending back to the early 1600s, it was not until Abbe, Schott and Zeiss joined forces in the 1880s that the art of optical design, fabrication and testing began a rapid transformation into a science.

The key to this transition was the ability to engineer the refractive index and the dispersion of optical glasses—a technology developed by Schott. While there was earlier work in the engineering of optical glass involving Stokes and Faraday and a lesser known scientist named Harcourt in the 1800s, and even earlier work by the French, Schott is the one that created a viable ongoing industry.

The first article in one of the first journals of science—*Philosophical Transactions*—is about the development of optical glass in France, "An Accompt of the Improvement of Optick Glasses" (*Phil. Trans.* 1665 **1**:2-3). The optics industry, which consists of several primary and often separable functions—optical design, fabrication, assembly and test—was fully emergent by 1900 based on surfaces that were firmly founded in rotationally symmetric spheres.

The fabrication of freeform surfaces for imaging applications using commercial equipment was enabled only in the last decade, ahead of both optical design tools and the optical testing community. This revolution will change these industries and the customers they serve forever.

Thinkstock/G.W. Forbes. Opt. Express **20**, 2483-99 (2012).

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Background and definitions

In the past, the label freeform was applied to fairly simple surface shapes, particularly toroidal surfaces, which only have a different radius along two orthogonal axes. This labeling was convoluted by the fact that the translation of the French term for an anamorphic surface (a more general form of a toroidal surface) is freeform. One of the earliest meetings to use the title was held in 2004 in association with the American Society of Precision Engineers, where a coauthor of this article (Thompson), working with J. Michael Rodgers of Optical Research Associates (now Synopsys Inc.), presented a paper on optical design methods for all-reflective optical systems with anamorphic surfaces titled, “Benefits of freeform mirror surfaces in optical design.”

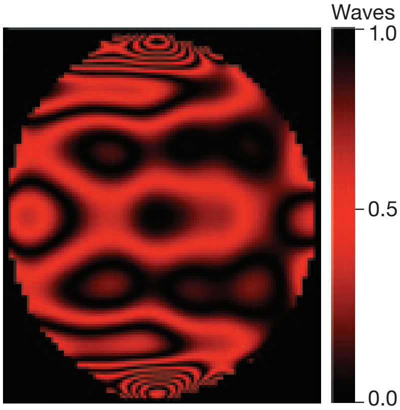
One of the first examples of the use of a true freeform surface in imaging optics was developed by James Baker working with Bill Plummer and Steve Fantone for Polaroid’s SX-70 camera. Prior to that, Luis W. Alvarez invented the variable focus lens for application in ophthalmology based on arguably one of the earliest freeform surfaces. (Here we are ignoring the history of progressive ophthalmic lenses that dates back to 1954 and Maitenaz.)

Alvarez was a Nobel Prize physicist who worked primarily on high-energy physics. He was brought to ophthalmics when his failure of accommodation caused him to pause. The day after his invention, he brought it to one of his graduate students, William Humphrey, who went on to pioneer many instruments in ophthalmology. The surface form that Alvarez introduced was, using his notation,

$$t = axy^2 + \frac{a}{3}x^3 - bx + c\,. \qquad (1)$$

This form of XY-polynomial surface in rectangular coordinates has maintained a position in the theory and application of freeform surfaces in ophthalmic and nonimaging/illumination applications. In illumination, the prevalence of XY-polynomial surfaces is a consequence of many applications that have a rectangular aperture rather than the circular one that is more common in imaging applications. While XY-polynomial surfaces are available in the imaging optical design environment, they are not an enabling form. They are not orthonormal over the commonly circular aperture of imaging optical systems; they are not used in optical surface testing; and they are not readily interpretable in the context of the historical theory of the aberrations of imaging optical systems.

Multicentric radial basis function (RBF) freeform surface



A simulated interferogram of the departure of a multicentric RBF freeform surface from a φ-polynomial surface.

Rolland and Cakmakci (2009)

Here we will put forward a modern definition of the term freeform in the context of optical surfaces used predominantly in imaging optical applications. Our modern definition is constructed by a definition not of what a freeform surface is, but, rather, by stating the technology that has enabled this revolution.

Freeform Optical Surface, Modern Definition (post-2000)

An optical surface that leverages a third independent axis (C-axis in diamond turning terminology) during the creation process to create an optical surface with as-designed nonsymmetric features.

Under this formulation, the most pervasive emerging class of freeform surface in imaging optics is the Zernike polynomial surface or its derivatives. That this type emerges first is a result of the fact that Zernike polynomials were adopted by optical testing companies in the 1970s and as a result are integrated with the optical analysis software environment and in some cases the imaging system optimization environment. The demonstration of this technology was led by Steve Patterson, now at UNC/Charlotte, who spearheaded the creation of the Large Optics Diamond Turning Machine at Lawrence Livermore from 1987 to 1988.

The first piece in this shape class was an asymmetric wavefront corrector. A second is the family of surfaces that fall under the heading of multicentric, radial basis function (RBF) surfaces. The key concept here, as recognized by one of us (Rolland) in 2002 and implemented in an optical system designed and fabricated by Cakmakci and Rolland, is the introduction of multicentric functions as an added layer on an optical surface shape that could range from a base sphere to a Zernike surface or the more recently developed Q-polynomial surface.

Multicentric RBFs consist of a series of basis form functions that, in the simplest structure, take on the size and shape parameters of a Gaussian (e.g., radius and standard deviation) function. Now, however, there are multiple additive basis functions that are “floated” out across the underlying parent surface where they then take up a position determined by the neighboring functions through optimization within an application space. These forms are currently being explored for application in head worn displays.

In the nonimaging community, the surface shape formulations that are emerging at the leading edge are often based in the non-uniform rational B-splines (NURBS) formulation. While Zernike formulations arose from optical testing, NURBS emerge from mechanical computer aided-design (CAD). The reason that NURBS do not reach into the imaging community is that they do not provide the necessary combination of speed and accuracy simultaneously. In addition, the technique for parameterization is cumbersome, requiring hundreds

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or thousands of parameters that need to be variables, often with associated constraints for optimization. The CAD of nonimaging systems is lagging that of imaging by roughly 10 to 15 years; a lack of a basis surface model with tractable parameterization is one of the reasons.

Conics and spheres

Historically, the first class of surface shape is spherical and conic surfaces, which were the dominant shapes until about 1980, particularly for large and modest aperture mirror systems. Telescopes are the predominant optical design. Galileo is often credited for inventing the first telescope based on lenses, but that appears to be a mistake. Hans Lippershey is the current choice of historians (see, for example, H.C. King); he is believed to have developed his instrument around 1610. Reflective telescopes appear in the literature in the earliest journals of science with publications of telescope forms that still dominate both the lexicon and the forms themselves.

While a Gregorian and Newtonian telescope were constructed shortly after they were proposed, the first Cassegrain telescope was built by Ramsden in the 1800s. The conclusion from this and reports published throughout the 1700s and 1800s (see R. Smith, 1738, and D. Brewster, 1830) is that the technology for conic mirrors existed throughout the period. The Cassegrain form, with its parabolic primary mirror, is the dominant type of telescope up to the Hubble Space Telescope in the 1990s. (The primary mirror is a defining feature, along with the convex secondary mirror, rather than the concave secondary of Gregory or the effectively plane secondary of Newton.)

The Hubble represents one of a few attempts to construct a Ritchey-Chretien form proposed in the 1920s. While the first generation of imaging telescope designs are corrected only for spherical aberration, the Ritchey-Chretien form also adjusts for coma, again using only conic mirrors, with a weakly hyperbolic primary mirror.

Rotationally symmetric aspheres

This is the second class of optical surface. In his 1899 patent, Ernst Abbe introduced the power series formulation for a rotationally symmetric asphere. These shapes occur infrequently until about 2000, when fabrication and testing methods became more advanced.

The commercialization of MRF technology by QED Technology, which has dramatically reduced the cost of the manufacture for glass components, has been significant to the introduction of this surface shape into mainstream optics. At the same time, the recent proliferation of cell phone cameras has driven further progress. These cameras are made from plastic components squeezed into compact spaces.

In 2008, Forbes noted that the optical design community, due primarily to a thought-to-be-trivial change in input and output formatting of optical design codes, was suddenly submitting optical surfaces described by 20th order aspheres for MRF fabrication. He reported a new form of aspheric surface definition that is formulated such that the coefficients that describe the surface are in units of sag.

This change clearly illustrates that, for most optical systems, no more than two to three terms in a power series definition should be active or fabricated. This discovery led to a second era for rotationally symmetric aspheres, under a formulation that has come to be called the Q polynomial form, introduced in CODE V based on Forbes' work.

Who's Who in Early Telescope Development

Wikimedia

Marin Mersenne

In 1636, a mathematician in communication with Descartes described two confocal mirrors making an afocal telescope (originally spheres, today associated with parabolas). It is still referred to as a Mersenne.

Wikimedia

James Gregory

He published the original two-mirror imaging telescope that carries his name (Gregorian) in 1670. This form was used most recently for the Large Binocular Telescope (LBT). It is longer than the more common Cassegrain, but provides a real exit pupil, which is necessary to effectively combine two paths.

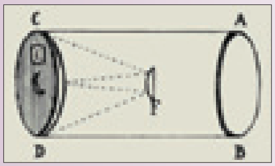
Wikimedia

Isaac Newton

His device is technically a one-mirror telescope, with a fold mirror, published in 1672. It is still popular among amateur astronomers.

Laurent Cassegrain

His telescope was described four months after Newton's in the *Journal des Savants*. It was the dominant form until the 1990s, when the Hubble was constructed. Little is known about Cassegrain, and no pictures of him exist.



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XY polynomials and off-axis conics

The XY polynomial, the third class of optical surface, is a unique surface shape that solves some specific problems. However, it is not part of the revolution that we are in today. It essentially adds some interesting new degrees of freedom in one dimension. However, optical design is, in almost all cases, a two-dimensional problem that requires a surface of revolution in 2-D.

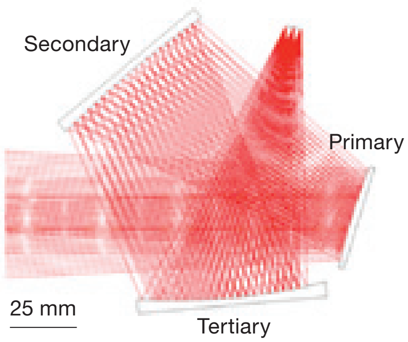
So-called "off-axis" conic surfaces comprise the fourth class. These are conventional conic surfaces edged with a large offset from the center of symmetry. In more extreme cases, they are fabricated with stressed polishing techniques perfected during the fabrication of the Keck telescope using methods attributed most often to J. Nelson.

What is becoming more common, however, is small-lap, computer-controlled polishing. Tinsley, which is now a division of Zygo, is often credited as an early successful developer of this technology. Their polishing of the nonsymmetric conic surfaces used for the COSTAR optics of the Hubble's first servicing mission is evidence of this. Off-axis conics initially appear as a result of attempts to correct the three primary aberrations (spherical, coma and astigmatism) for astronomical applications by moving from optical systems with two mirrors, with two conics as free parameters for aberration correction, to those with three.

Initially, Meinel and Shack, and astronomers such as Rumsey, introduced three-mirror anastigmats, typically with large obscurations. One of the earliest public documents that illustrates the use of off-axis conic mirrors is a 1972 patent by Offner. It only reveals afocal forms, leading one to hypothesize that the focal forms were investigated, but not published at that time. Offner is best known as the optical designer of an all-reflective spherical mirror system that used an offset field, a concept that may have originated with Rod Scott of Perkin-Elmer.

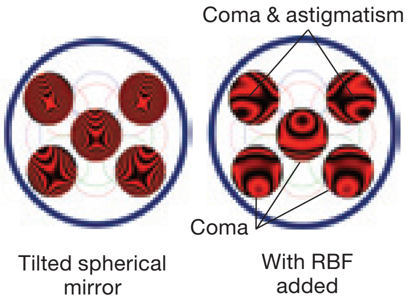
In the 1980s, the advent of the Strategic Defense Initiative—more commonly known as the Star Wars program—sparked the design community's interest in the unobscured telescope form based on fundamentally off-axis conic mirrors to reduce stray light. Lacy Cook working at what was then Hughes patented a number of forms, including the one most often referred to as the "Cook reflecting triplet" three-mirror anastigmat (TMA). (This was a coincidental parallel to the ubiquitous "Cooke refractive triplet" of the late 1800s, which was patented by Dennis Taylor while working for Cooke.) In 1990, Figoski published an early report of a successfully built TMA. At this point, optical alignment and testing began to emerge as a limiting factor in advancing the technology.

[φ-polynomial surfaces]



Fuerschbach, Thompson and Rolland (2011)

[Multicentric radial basis functions]



Bauer and Rolland (2011)

While Cook was using somewhat conventional optical design methods on an internal software package (Hexagon), simultaneously, one of us (Thompson) was developing methods for the optical design of a nonsymmetric optical system based on R.V. Shack's discovery of nodal aberration theory (NAT) in 1977. This was then expanded from a concept to a complete theory of the aberration fields through 5th order of nonsymmetric optical systems. This work was completed in 1979, but only recently made its way to the literature.

In the context of modern freeform optical surfaces, NAT reported to date, with one exception, requires that the surfaces under study be sections of rotationally symmetric conics or aspheres. An important development was the introduction of the full field display—a new optical system analysis feature that provides a visualization of the nodal field properties of specific aberration terms in terms of the FRINGE Zernike polynomial characterization of the aberrations published at the 1985 optical design conference. This feature, which had a compute time of more than 30 minutes when introduced, can now fully characterize even the James Webb Space Telescope's NIRSPEC camera in seconds. In August 2011, Sagem completed four aggressively configured TMAs in a chain on NIRSPEC.

Shack's discovery of the nodal aberration field property of optical systems without symmetry was based on a fundamental concept by Buchroeder. It will become a key enabler for the optical design of the coming generation of freeform optical surfaces. A recent discovery by K. Fuerschbach, working in collaboration with us, has removed the limitation that NAT could only be applied to intrinsically rotationally symmetric surfaces.

This last fundamental discovery, which has been 35 years in the making, leaves the optical design community fully prepared to develop the necessary optical design and analysis environment to successfully exploit the new optical design degrees of freedom brought forward by the modern definition of freeform surfaces. This work is essential in order to avoid becoming disoriented by all of the apparently new parameter spaces. What used to be simply a radius and a conic constant has become a myriad of surface description parameters to

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To some extent, the two mirror telescopes that were discovered in the 1670s were perfected in the later part of the 1900s. Three mirror anastigmats, on the other hand, were invented in the 1960 to 1985 timeframe. They were first shown in public as a subscale level in a prototype in 1990 in the paper by Figoski. The most significant challenges in perfecting this technology in the end were related to aligning and testing the off-axis components in the TMA.

Sagem's success in developing TMAs for the James Webb telescope, under the leadership of R. Geyl, completes the evolution for this class of optical surface shape. All aspects of the design, fabrication, test and assembly have been successfully demonstrated in a cost-/profit-driven environment—a good working definition of a mature technology.

Rotationally nonsymmetric polynomial aspheres

The fifth class of optical surfaces, which is a subclass of a freeform surface, are rotationally nonsymmetric polynomial aspheres, or more specifically φ-polynomial aspheres; Zernike polynomials are a significant subcategory. To trace the evolution of this form, we must look to the optical component fabrication community for the initiation of the relevance of this surface to optical systems.

The key development comes with the introduction of slow servo (also called 5-axis, and C-axis) in the commercial diamond turning community around 2002. This actively emerging technology is going to change the world, and quickly. It will lead to aggressive innovation in optical design, fabrication and particularly optical testing. One of the first full cycle pathfinder systems is based on a design by Fuerschbach and Rolland. It is expected to be completed as a prototype demonstrator of all aspects of the technology, similar to the Figoski TMA prototype of 1990, in 2012/13. No other optical system has been successful in placing the key optical parameter of a surface, the center of curvature, significantly away from the optical axis. This important packaging degree of freedom is fully enabled by φ-polynomial surfaces.

This is a true revolution. Until 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 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 amount of spherical aberration introduced at a surface. Particularly for the important class of off-axis, all-reflective, unobscured systems, which are a key to the future of optical lithography, this condition has locked EUV technology in a box well short of what is commercially feasible for over 15 years.

Freeform surfaces described by φ-polynomials are under active development and integration in all aspects—optical design, optical fabrication, optical component testing, optical system alignment and optical system testing. The current focus is to move the wavelength at which these surfaces are diffraction-limited down from the current region, arguably 1 μm, all the way to 13 nm (for EUV lithography) and beyond.

The most significant impediment to progress is the optical testing of these surfaces. The preferred method for imaging optics is interferometry, which limits the maximum slope that a surface can contain. Fundamentally, the optical surface is imaged onto a digital camera that restricts the density of fringes. Two independent solutions emerged recently (Zygo's Verifire and QED's ASI) that expand the surface slope that is allowed, but further dynamic range is needed.

At the same time, each and every community along the supply chain must learn new concepts and develop new tools to leverage these revolutionary shapes. It is a new dawn. ◭

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

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OSA Incubator Meetings

This article provides a historical context that will inform next month's feature summarizing work presented at OSA's recent Incubator meeting on freeform optics. OSA recently initiated this new form of meeting to provide unique and focused experiences, giving researchers in niche fields an opportunity to discuss advances, challenges and opportunities regarding their research. Jannick Rolland is leading the development of this exciting program.

OSA Incubator meetings:

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