A Jewel in the Crown II
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16. The Freeform Optics Revolution

Jannick P. Rolland

Short Biography and Notes

Jannick Rolland received a master’s in optical engineering from The Institute of Optics in Orsay, France, and a PhD in optical science from the University of Arizona. She joined The Institute of Optics at the University of Rochester in January 1209 under the directorship of Wayne Knox (BS ’79, PhD ’84).

Rolland’s thirteen-year professional academic path prior to joining UR had led from assistant professor to full professor at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida.

On April 19, 2009, Rolland was endowed as the Brian J. Thompson Professor of Optical Engineering at UR, a humbling moment in her scientific career. John Bruning, former CEO of Corning Tropel and a lifelong friend to UR and The Institute, honored Brian Thompson’s achievements with the creation of this chaired professorship. Jannick was appointed director of the R. E. Hopkins Center in July 2012 when Xi-Cheng Zhang took office as director. Rolland is grateful for having been part of these various sanctuaries of optics spanning France to the Wild West, to the Far South and finally to the Great North.

Rolland’s entry into Optics at The Institute of Optics in France was through a path less traveled. She was admitted to the grandes ecoles, the “agreed-upon” elite schools in France, having declined an offer from the Institut Universitaire de Technologie (IUT) Measures Physiques in Orsay, France. After a long three weeks spent in Grande Ecole Carneau in Paris, she decided to reconsider and approached the IUT in person. The connection through her optics professor, Jacques Serres, at the

Figure 16.1. Jannick Rolland, Brian J. Thompson Professor of Optical Engineering. Photo by J. Adam Fenster/University of Rochester.
IUT Measures Physiques combined with her love for mathematics led her to apply to The Institute of Optics in Orsay two years later. Her admittance was unpopular with a couple of professors, even though she was a valedictorian. However, Michel Cagnet, astronomer and directeur des études at The Institute of Optics in Orsay, known for cowriting the *Atlas of Optical Phenomena*, admitted her following an oral exam and an interview. This opportunity seeded her career as an optical engineer.

Rolland’s move to the United States in her early twenties stemmed from her intuition that moving deeper out of her comfort zone (first experienced with admission against the will of a couple of faculty), together with learning how to communicate fluently in English, would be critical skills to learn in either of the two professions she still considered: optics or professional dancing. It would require further development of the adaptation gene, which Rolland thinks turned out to be essential along her path. Wouldn’t it be nice to satisfy that quest while doing optics and dancing? Rolland applied to the College of Optical Sciences at the University of Arizona, originally driven to explore her interests in space optics and dancing—and met with an inevitable culture shock. She graduated in 1990 with her PhD in optics with a focus on medical imaging, working with Prof. Harry Barrett as her adviser.

**Rochester, New York—a Magnet for Optics**

Rolland’s move to Rochester, New York, in 2009 was guided by her strong drive to accelerate the emergence and impact of two technologies: a biomedical optics
technology, *Gabor domain optical coherence tomography (GD-OCM)*, and *freeform optics*. Rolland invented GD-OCM around 1996, which achieves high-definition volumetric subsurface optical sectioning at the cellular level together with nanometer-class thickness estimation. The magnet in Rochester for Rolland was the rich optics industry ecosystem that grew out of the success of Kodak, as well as a medical school across the street from The Institute of Optics, which is highly ranked in research innovations. A NYSTAR Foundation career award (i.e., an approximately $1 million joint investment between the State of New York and the University of Rochester) seeded Rolland’s rapid progress with her team in these two fields of research. One led to the start-up LighTopTech (www.lightoptech.com), incorporated in May 2013 with cofounder Cristina Canavesi, Rolland’s first PhD graduate at The Institute, and the other to the Center for Freeform Optics (CeFO), awarded a grant by the National Science Foundation on August 1, 2013, for five years, and renewed September 1, 2018, for five more.

**Optical Design, a Legacy at The Institute of Optics in Rochester**

The Institute of Optics at the University of Rochester has a long legacy of teaching optical system design. Rudolf and Hilda Kingslake joined the university in 1929 at the founding of The Institute of Optics, followed by Robert E. Hopkins (MS ’39, PhD ’45) in the early years of The Institute. Rudolf Kingslake is regarded as the father of lens design, and his book *Lens Design Fundamentals*, along with Conrady’s contributions to the field (published in Part I of the book), have served as references to lens designers for approaching a century.\(^1\)

Since 1998, Julie Bentley (BS ’90, PhD ’95) has been teaching the foundations of optical system design to both undergraduate and graduate students at The Institute. These foundations have focused (in large part) on rotational symmetric systems. First published in 2012, Bentley’s *SPIE Field Guide to Lens Design* is expected to support the education in foundations of optical system design for generations of students to come.\(^2\)

While optical system design was popular from 1930 to 1960, with the invention of the laser, the field of optical system design slowly took a plunge until recent years. Attracting students to study this field of engineering became a challenge as the laser quickly became a hot topic in both its further developments and exploding applications. Pioneers in laser engineering Gérard Moreau, professor at The Institute of Optics in the 1980s, and Donna Stickland (PhD ’89) won the Nobel Prize in Physics in 2018.

As all comes in cycles, “lens” designer, a profession that may have been thought to be coming to the brink of extinction in the twenty-first century, is now one of the most in-demand specialty fields among broadly trained optical engineers and is attracting strong young talent to this field.
Reflection on the Birth of Freeform Optics in Rolland’s Laboratory

The intersection of our passions appears to be key in sustaining the drive in research. Rolland will now highlight an early connection to freeform optics.

In 1990, after graduating from the University of Arizona, Rolland took another path less traveled and joined the Department of Computer Science at the University of North Carolina to design head-worn displays for medical visualization. She had just graduated with her PhD in optics and spent the next six years as the only optical engineer working with computer scientists leading research in Augmented and Virtual Reality. It was simultaneously an amazingly challenging and exciting time.

Perhaps it was serendipity, but another group at UNC, the Vision Group, was conducting research in 3D shape perception, which fascinated Rolland to the point that, after one and a half years doing optical system design, she decided to diversify her efforts and agreed to lead the Vision Group. This period seeded her curiosity in the mathematical definitions and perception of complex shapes we call today freeform optics. Rolland first pursued her interest in optical metrology of freeform optics a few years after joining CREOL at the UCF in 1996. In 2005, Rolland started working on optical design with freeform surfaces, which rapidly pointed to the opportunity and challenge ahead.

Nodal Aberration Theory Seeded the Development of Freeform Optics

Between 1978 and 1980, driven by the needs of the astronomical community, nodal aberration theory (NAT) was invented at the University of Arizona by Roland Shack, and Kevin Thompson developed NAT up to the fifth order. NAT expands the conventional aberration theory of H. H. Hopkins to rotationally nonsymmetric systems, and was specifically targeted to account for misalignment-induced aberrations.

Rolland (Jannick) started working with Thompson (Kevin) in 2006, partnering in science and in life. Jannick and Kevin collaborated in applying NAT to understand the optical aberrations of off-axis optical systems as well as misaligned systems. When Jannick joined The Institute of Optics in 2009, Kevin was working for ORA-Synopsys, but he also joined The Institute as a visiting scientist. On August 20, 2009, Kevin and Jannick were married at the Eastman House among family and friends, including the late Emil Wolf and his wife, Marlies, who lit up our Institute for many years.

Joining The Institute of Optics at the University of Rochester in 2009 fast-tracked Jannick and Kevin into the future, as they were already working with Rochester-based companies in freeform optical manufacturing. What may have been specified as a smooth freeform surface in design was manufactured, in fact, as a diffraction grating. The tool artifacts, expressed as fine lines created during diamond turning referred as midspatial frequencies (MSF), were severe. Two
NSF program directors, Dr. John Zavada (PhD ’71, New York University) and Dominique Dagenais (MS ’76), recognized the innovation in freeform optics and awarded Rolland, as principal investigator, and Thompson, as co-PI, a GOALI grant (2010–13). This was conceived in partnership with Optical Research Associates (ORA), a division of Synopsys since 2010, as the lead company on the topic of freeform optics that seeded the early work in this field at The Institute. Also, the II-VI Foundation funded Rolland through the block-gift program from 2010 to 2020 on projects related to freeform optics.

In 2010, Thompson and Rolland, working with Fuerschbach (PhD ’14), realized the far-reaching importance and role that NAT may have in understanding the aberration theory of freeform optics essential in the design of freeform optical systems.6

Between October 30 and November 1, 2011, fifty-four experts in optical design, optical fabrication, and testing from academia, industry, and governments labs, national and international, gathered in Washington, DC, for the first Optical Society of America (OSA) incubator meeting, a new type of meeting Rolland led while serving on the OSA board of directors in 2010–13. Freeform Optics was the topic of the inaugural meeting.7

The Center for Freeform Optics

At the beginning of the twenty-first century, something highly unexpected took place: the “Freeform Revolution.”8 Here the word is chosen from the perspective of a technology that is over one hundred years old: the freeform optical surface. The fabrication of high-precision freeform surfaces required for imaging applications was practically enabled only in the last two decades, both by optical design tools and by optical testing. This revolution will forever change these industries and the customers they serve.

A freeform surface is an optical surface that requires a third independent axis (C-axis in diamond-turning terminology) during the fabrication process to create an optical surface whose surface shape lacks translational or rotational symmetry about axes normal to the mean plane. In the recent past, the denomination freeform was (erroneously, from a design point of view) given to surface shapes, such as toroidal surfaces and off-axis conics, that break rotational symmetry.

In fabrication, an off-axis conic made without first creating the parent optics, is considered a freeform surface by fabricators. In design, however, this surface shape does not have the degrees of freedom required to correct the optical aberrations of 3D folded systems and as such falls short of being considered a freeform surface.

The community of research engineers and scientists expressing an interest in freeform optics grew rapidly in the first ten years, which led Rolland and a team of collaborators across the Departments of Optics and Mechanical Engineering as well as the Laboratory for Laser Energetics to propose a Center for Freeform Optics to the National Science Foundation.
CeFO was awarded a grant by the NSF on August 1, 2013, with the headquarters in Rochester (focused on design and metrology) and a site partner at the University of North Carolina at Charlotte (focused on optical and optomechanical manufacturing). Rolland (Optics) has led CeFO since 2013 with Associate Director John Lambropoulos (Mechanical Engineering). At UNC-Charlotte, the center was served by Angela Davies (Optics) (2013–15), with Associate Director Christopher Evans (Mechanical Engineering), followed by Matthew Davies (Mechanical Engineering) (2015–18) and Associate Director Thomas Suleski (Optics), who took the directorship in 2018 with Associate Director Konstantinos Falaggis (Mechanical Engineering). The partnership between Optics and Mechanical Engineering is central to CeFO and has enabled concurrent engineering that is essential to advancing the technology-readiness level of freeform optics. Other faculty partners of The Institute in the center from 2009 to 2019 include Profs. James Fienup and Miguel Alonso, whose research in freeform optics is featured later in this chapter.

The vision of the Center for Freeform Optics is that compact, affordable, and perfromant optical systems will permeate precision technologies of the future. Its mission is to advance research and education in the science, engineering, and applications of systems based on freeform optics through a dedicated, continuing industrial partnership based on shared value.

A major interdisciplinary research program emerged with, on the academic side, twenty-one faculty members and thirty-four students comprising 40 percent underrepresented minorities and a majority of women. On the corporate and government side, seven pioneers (Air Force Research Lab, Ball Aerospace and Technologies, Optipro Systems, PolymerPlus, Rochester Precision Optics, SCHOTT North America, and Zygo) joined CeFO to enable its launch, with support from the National Science Foundation.

From 2013 to 2019, a total of twenty-six members partnered with CeFO (the seven pioneers as well as Aperture Optical Systems, ARRI, Collins Aerospace, Corning, Eminess Technologies, Facebook Reality Labs, Google, Jabil Optics, JPL, LightPath Technologies, L-3 Communications, Microsoft, Nikon Research Corporation of America, OptoAlignment Technologies, PerkinElmer, Poco Graphite, Synopsys, Thales, and Zeiss). Also, NASA has been supporting selected students with fellowships to advance freeform optics for space science.

An expansion into the curriculum was soon initiated by Rolland in Fall 2016, with a new course in Freeform Optics that spans from historical highlights to hands-on optical system design with freeform surfaces. In January 2019, Aaron Bauer (PhD ’16) joined Rolland to coteach the course and facilitate hands-on workshops using CODE V optical design software. One of the longest-lasting effects of CeFO is the development of a new generation of young scientists broadly educated in freeform optics. The students, ranging from undergraduates to masters to PhDs to postdocs, represent a broad spectrum of backgrounds. Importantly, the constant contact with industry as well as CeFO faculty represents a new model of learning.
for all students involved in the center, where industry itself is the third partner in the student-teacher intellectual relationship.

Freeform optics is poised to permeate all precision technologies of the future, and perhaps a lot sooner than we ever anticipated.

**Freeform Optical Design: Jannick Rolland and Kevin Thompson**

A foundation in optical system design, whether the system leverages rotationally symmetric or sections of rotationally symmetric surfaces, or freeform surfaces, is to start the design process with TABLE 1, a short name for Table of Specifications that solely requires first-order computations. The term TABLE 1 was cast by ORA, led by Robert S. Hilbert (BS ‘62) (MS ‘64) as president from 1991 to 2008, a lifetime partner to The Institute. Kevin Thompson (PhD ‘80, University of Arizona) led the ORA Engineering Group as vice president of engineering and shared these best practices with students. ORA was one of a handful of companies to advance the development of optical design software from mainframes to the personal computer.

Early on at The Institute and elsewhere, the research effort focused on the mathematical surface descriptions of freeform optics. The research also started to investigate methods of optical system design with freeform surfaces. The first freeform imager, Pathfinder 1, a F/1.9 long-wave infrared imager, was designed at The Institute, fabricated at II-VI Infrared, and tested at The Institute. To point to its size, Rolland referred to Pathfinder 1 as “pamplemousse,” the French counterpart to “grapefruit,” to communicate intuitively the approximate volume of the system.

At Rochester, Jannick and Kevin with graduate student Fuerschbach focused their next efforts on the derivation of aberration theory for freeform optics, and with graduate students Bauer (PhD ’16), Eric Schiesser (PhD ’19), Jonathan Papa (PhD ’20), Nicholas Takaki (PhD ’21) on design methods. In Rolland’s group—graduate students Jianing Yao (PhD ’16), Di Xu (PhD ’20), and Romita Chaudhuri (PhD ’21)—has significantly advanced the metrology of freeform optics.

In the second phase of CeFO (2018–23), we are applying the existing and emerging methods to a wide range of optical systems addressing the various needs from space optics to microscopy. We are steadily advancing high-precision...
manufacturing of freeform optics across a diversity of materials. On the roadmap are plans to advance the precision manufacturing of diamond-turning-based methods as well as volume manufacturing through high-precision molding and replication. High-precision metrology of freeform optics is probably one of the toughest challenges. Various approaches are being developed in parallel, and the layout of a metrology roadmap for both existing and emerging methods is being developed to detail a pathway to advance the technology-readiness level of freeform optics necessary to permeate various markets.

Mathematics of Midspatial Frequencies: Miguel Alonso

The group of Miguel A. Alonso (PhD ’96) began in 2016 a project with the goal of giving a simple and intuitive description to MSF errors and their effect on the performance of optical systems. Participants in this research included Alonso as well as graduate students Kevin Liang (PhD ’20) and Wenhua He (MS ’18), as well as two external collaborators: Gregory W. Forbes (a former professor at The Institute of Optics) and Thomas Suleski (UNC-Charlotte). The idea was to combine ray and wave optical theory with elements of basis representations, probability, statistics, and geometry to arrive at simple rules of thumb that not only give quantitative predictions but also (and perhaps more importantly) an intuitive picture of the effects.

One of the main thrusts of this project was to define new quantities that provide a link between the probabilistic nature of surface errors and standard optical performance metrics. This began with a study of the Strehl ratio by Alonso and Forbes, which was later extended by Liang and Alonso to the description of more general image-quality measures such as the optical transfer function (OTF) and its link to MSF through the definition of a new quantity, the pupil-difference probability density (PDPD). This description was used to study the MSF structure resulting from turning and milling processes, and even simple aberrations. In combination with simple geometry, this approach led to simple closed-form accurate estimates of the OTF. These results were validated against more numerically intensive simulations in collaborative work with Suleski and his PhD student Hamidreza Aryan.

A second thrust of this work was to understand and evaluate the accuracy of a standard perturbative approximation used in the study of optical systems with
MSF errors. The effects of aberrations and other errors on the wave-optical performance of a system are particularly easy to model when those errors are assumed to be placed at the exit pupil of the system or a plane conjugate to it, since then they can be accounted for by a phase over the field at the pupil, from which the point spread function (PSF) is obtained through simple Fourier transformation. However, typically, the phase errors caused by surface deviations such as MSF are not at a plane conjugate to the pupil but at several different planes along the system. The standard approximation is then to drag these errors to the pupil along the system’s nominal rays, so that a Fourier transformation can be used to estimate the PSF. Liang, Forbes, and Alonso provided a careful study of the validity of this approximation and found simple and intuitive rules of thumb for what level of error it introduces. As a side product, their work on this topic gave rise to a new complete orthonormal basis set (an alternative to the Zernike and Q polynomials) for the study of phase errors.

**Phase Retrieval for Freeform Metrology: James R. Fienup**

In a number of different disciplines, one wishes to know the wavefront of an optical field, which is directly related to the phase of the field, despite making only measurements of the intensity of the field, referred to as the problem of phase retrieval. Application areas include, for example, coherent X-ray diffractive imaging (crystallography without requiring crystallization of the sample) and image reconstruction for optical astronomy and microscopy. A third application area is for wavefront sensing. In 1990, we were able to determine the phase aberrations of the Hubble Space Telescope from measured intensity images of stars taken with the telescope; knowledge of the aberrations allowed optical engineers to make correction optics that were installed into Hubble that have since given us the wonderful pictures of the cosmos that have inspired us all. Based on that experience, NASA and its contractors built the James Webb Space Telescope (JWST), which totally relies on phase retrieval in order to operate, with its primary mirror consisting of eighteen separate segments, to be accurately aligned in space. For more details on the JWST, see Essay V.20 by David Aronstein.

We decided to apply related techniques for the difficult task of the Center for Freeform Optics to develop approaches to accurate optical metrology on freeform surfaces being manufactured.

Aaron Michalko (PhD ’20) and his adviser, Prof. James R. Fienup, the Robert E. Hopkins Professor of Optics (since 2002), began work on this project in the fall of 2015. They employed a particular phase-retrieval approach called transverse translation diverse phase retrieval (TTDPR) (or ptychography). As illustrated with the cartoon (fig. 16.6), it involves illuminating one part of the freeform surface at a time, and collecting a splotch of light reflected to the plane of a detector array. The illumination beam is scanned over the surface
with overlapping illumination patterns, and the resulting collection of splotches of light goes into a nonlinear optimization algorithm that determines which one optical surface is consistent with producing all those splotches of light. This approach uses an absolute minimum of optics, which makes it potentially much less expensive than other metrology approaches, and it minimizes the need to characterize the system’s optics. Since no reference beam is involved as in interferometry, it should be relatively tolerant to vibrations and does not suffer from retrace errors.

Investigation into this technique has been performed both in simulation and in the laboratory. Through simulations, the algorithm has been shown to work with soft-edged illumination beams as well as in the presence of large aberrations, which are expected when testing nonspherical optics. In the lab, the method was verified against standard metrology and tested on a freeform surface. This technology could be an enabler for wider use of freeform optics.

Notes


