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Freeform Optics: Notes from the Revolution

Driven by advances in theory, computational speed, and design and fabrication ingenuity, freeform surfaces continue to make inroads in a range of applications.

Stewart Wills

Five years ago in these pages (OPN, June 2012, p. 30), Kevin Thompson of Synopsys Inc. and Jannick Rolland of the University of Rochester, N.Y., USA, wrote of a revolution sweeping through optical imaging design: freeform optical surfaces. A combination of theoretical advances, improvements in computational speed, and better capabilities for fabricating asymmetric optical surfaces was, they suggested, spurring new opportunities for compact, high-performance optical designs in a range of applications. And, Thompson and Rolland argued, to take advantage of these revolutionary shapes, "each and every community along the supply chain must learn new concepts and develop new tools."

So where does that cross-industry revolution stand five years later? To find out, OPN talked with a number of experts in freeform-optics research, design and fabrication. We learned that the freeform revolution is alive and well, is spurring new forms of collaboration, and could, over the next few years, increasingly reshape the way optical elements are made and deployed.

Defining freeform optics

The simplest definition of a freeform optical surface is one that lacks translational or rotational symmetry—and that broad classification provides a hint of why it has historically been so difficult to create such surfaces.

In the imaging subdomain in particular, optical systems, both spherical and aspheric, "have traditionally had an axis of symmetry," notes Gregory Forbes, a freeform-optics pioneer who now leads the Australian firm Scisense Consulting. "Their shape can be

(Facing page) Deterministic polishing of a large-aperture lens using magnetorheological finishing. QED Technologies

Compact freeform lens for a fog light. Fraunhofer Institute for Laser Technology ILT, Aachen/Germany

described by just a single curve spun about an axis, and the fabrication and testing of such shapes can be simplified by exploiting that symmetry." Freeform surfaces, Forbes says, create new possibilities by allowing that symmetry to be broken.

A more mathematical definition of a freeform surface, adds Fabian Duerr of Brussels Photonics (B-PHOT), Vrije Universiteit Brussel, Belgium, might be an optical surface whose surface function requires two variables—angle and radius, for example, or *x* and *y*—rather than one. The category "freeform optics," says Jannick Rolland, who directs the Center for Freeform Optics (CeFO) research consortium, includes optical designs with at least one such freeform surface.

The operational, day-to-day definition of freeform, however, can depend on whom you're talking to. "What is freeform? I think the answer depends on whether you're an optical designer or a fabricator," says John Rogers of Synopsys Inc. A designer, he explains, will view any piece that in itself isn't rotationally symmetric as a freeform surface. But a fabricator might call the same piece freeform or rotationally symmetric, depending on how it's actually made.

Jessica DeGroote Nelson, the Director of Technology and Strategy at the fabrication firm Optimax, offers an example. "At Optimax, we've defined freeforms both by their lack of symmetry and by the fabrication method," she explains. "An off-axis parabola manufactured as a parabola—the parent piece—with the off-axis child piece cut off, would be classified as an asphere. However, if we were to manufacture the off-axis parabola by itself, it would be classified as a freeform."

Freeform's advantages

Whether they're defined mathematically or operationally, the increasing ability to embed freeform shapes into optical systems allows "various gains to be won," in Forbes' words. Strictly speaking, the idea of such gains is nothing new. Progressive ophthalmic lenses require freeform surfaces (one reason they have been so expensive to make), and the legendary Polaroid SX-70 instant camera developed in the 1970s used off-axis aspheres that were "not figures of revolution," and that today would be called freeforms. What's different now is how a combination of theory, computer power, innovative fabrication, and a growing design consciousness of these surfaces' potential are coming together to create new opportunities.

One situation cited by Duerr involves multimirror systems, in which freeform's ability to work off-axis can make all the difference. "You might have a design with two, three or more mirrors that you somehow want to

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create in space, but with an on-axis system the light fields are blocked by the elements themselves," he says. "If you want to achieve such a system you need to start tilting your mirrors in 3-D. You need to go off-axis, and so you don't have rotational symmetry anymore. That's what freeform can really do—deliver tailored solutions for nonsymmetric optical systems."

Rogers says that such an ability is "a design tool that we could only sort of dream about back in the 1980s"—and adds that it carries some unforeseen benefits in practical areas, such as alignment sensitivity, when the system is actually being assembled. "Freeform gives you extra degrees of freedom," he explains. "And it turns out that if you have the right tools to see the system's sensitivity, you can actually use those new degrees of freedom to make the system *less* sensitive to alignment if it's freeform" than an on-axis, symmetrical system would be.

"What is freeform? I think the answer depends on whether you're an optical designer or a fabricator."

—*John Rogers*

Expanding application space

Beyond making such systems possible at all (and, perhaps, less sensitive to alignment error), freeform surfaces can deliver performance gains of more than 50 percent, according to Rolland, "using various metrics like increased field of view, larger spectral band, increased light throughput and higher compactness." She points to a recent example from her own research team: a set of spectrometer designs using freeform or hybrid spherical-freeform gratings that achieved a threefold increase in spectral bandwidth and a fivefold increase in compactness relative to non-freeform designs.

Freeform surfaces have come into their own in other areas with tight packaging requirements—particularly in virtual-reality and augmented-reality (VR/AR) head-up displays, where, says Forbes, freeform surfaces allow the ray path to be folded up compactly. (Indeed, Rolland notes that the need to create a more "socially acceptable," sunglass-like format for AR headwear was a main reason her group first undertook freeform-optics research a decade ago.) Freeforms also, Forbes adds, "enable distortion correction and uniform illumination in short-throw projection systems." Nelson of Optimax points out that freeform surfaces could prove a key enabling technology in other emerging tight-fit applications, such as optics for unmanned aerial vehicles (UAVs), or drones, and compact imaging instruments for CubeSat missions.

Freeform design has become central as well to some systems that aren't exactly compact. The behemoth primary mirrors of next-generation telescopes, including the Giant Magellan Telescope, have off-axis designs requiring freeform or locally freeform surfaces; indeed, the construction of these telescopes has significantly pushed forward aspects of freeform-optics fabrication.

Finally, while the field may be going in a different direction, Forbes notes that extreme-ultraviolet (EUV) lithography also benefits from freeform elements. "In EUV lithography, a bare minimum of mirrors is beneficial, due in part to reflection losses," says Forbes. "A folded-up path to deliver extreme performance demands as many degrees of freedom in each mirror's shape as possible."

Fabrication advances

Getting these and many other once exotic freeform visions to routine production reality has required dynamic advances in both design and fabrication. It has also, according to the experts we spoke with, called for new levels of cooperation and interaction among those communities.

The workhorse of freeform-surface creation remains the multi-axis, computer numerical control (CNC) diamond turning machine, for basic turning, milling and grinding of many optical elements. These machines, notes Rogers, produce surfaces that are in the simplest case axially symmetric, but the tool tip can be actuated harmonically in the z direction to create more complicated shapes defined by variations in radial position and azimuth angle. (The Zernike polynomials, a commonly used mathematical description for freeform surfaces, constitute one example of such surface types.)

But other approaches highly relevant for freeform fabrication—especially ones focused on the polishing and finishing steps of the process—have also emerged in the past two decades. One of the more influential has been magnetorheological finishing, originally developed in the Soviet Union in the 1980s, advanced in the 1990s in work at the University of Rochester, USA, and brought to market in 1998 by QED Technologies.

The method, explains Rogers, involves a rheologically tuned fluid that stiffens under an externally applied magnetic field, and into which grinding or polishing particles have been embedded. A computer-controlled tool, tied to a digital "error map" of the part, delivers the liquid onto the part's surface, where a localized magnetic field stiffens the material and allows it to polish the part at the right place. When the field is removed, the material becomes liquid again and is drained off for reuse.

"That's what freeform can really do—deliver tailored solutions for nonsymmetric optical systems."

—*Fabian Duerr*

Another fabrication method, developed at the University of Arizona, USA, for fashioning large-telescope optics such as those on the Daniel K. Inoyue Solar Telescope and the Giant Magellan Telescope, involves the use of a deformable, non-Newtonian/viscoelastic material embedded in a polishing lap. The shape of the lap conforms to the surface of the giant optical element, with the amount of polishing controlled deterministically according to a dwell-time map. As interest in freeform optics has grown, still other techniques have become available, notes Rolland, including ion beam polishing (pioneered by R. Levi Setti), ultraform finishing (developed by OptiPro Systems), reactive atom plasma technology (from the Lawrence Livermore National Laboratory), and laser polishing.

Materials, of course, also play a role in how freeform optics are created. Molded plastic, for example, can fashion freeform optics—though, as Rogers points out, the mold itself will usually be diamond-turned, and thus "whatever technology limitations there are for diamond turning are going to apply to the molds." Rolland notes that if such molds or master stamps can indeed be fabricated at sufficient accuracy and in suitable materials, then replication or molding of polymers, glass, or other materials could ultimately be what drives mass production of freeform optics—a problem on which she says her group is actively working now.

The design-production nexus

Perhaps the largest challenge in fabrication is the sheer diversity implied in the word "freeform" itself. "No two freeforms are the same," observes Nelson, "and many times they are not even similar." Moreover, the "solution-space envelope"—the set of design requirements that fabricators must respond to—provides a rapidly moving target. "Initially it was small," Nelson says, "but it's been growing exponentially in the past five years." Devising flexible fabrication approaches that can respond to those challenges, and still maintain high production volumes, remains a continual challenge, and a key driving force in fabrication technology.

That challenge cuts both ways, however. Rogers points out that the capabilities, equipment and specific techniques used by the fabrication partner inevitably put constraints on what the designer is allowed to do, and what workarounds or alternative recipes the design process might need to explore. For example, the slow-tool servo method of diamond turning—which has been used to build systems that allow the highly off-axis optics that have proved crucial in moving freeform surfaces forward—has, according to Rogers, a limited ability to do surfaces with high azimuthal dependence. Such surfaces require the alternative, fast-tool servo method—which cannot offer features as deep as the slow-tool method.

Those sorts of considerations, and many others, place a huge premium on communication between the designer and the fabricator. "Sometimes, in giving presentations on this, I describe a technological innovation that's absolutely essential for these sorts of things—it's called the telephone," says Rogers. "If the designer is talking to the fabricator during the design process, there aren't going to be any surprises, which are never a good thing."

Fortunately, partly driven by the demands of freeform optics, close cooperation and communication between the design and fabrication communities has become increasingly commonplace—and the benefits go beyond just avoiding surprises on a particular optical part. "I think there's a healthy collaboration between these groups, especially when working with freeforms," says Nelson. "Both designers and fabricators are learning from each other. And typically the best solutions come when they work together as early in the process as possible." Duerr—who says that such links, always important, have become even more so in the freeform age—concurs. "We try to make designs they can manufacture and assemble," he says. "But at the same time they try to improve the fabrication facilities and methodologies to make our designs. It's a really nice way of pushing each other."

"I think there's a healthy collaboration between [designers and fabricators], especially when working with freeforms."

—*Jessica DeGroote Nelson*

Rolland sees this productive tension between the design and fabrication communities as an excellent example of "concurrent engineering," a concept she attributes to Christopher Evans, who directs the Center for Precision Metrology at the University of North Carolina, Charlotte (USA). "Concurrent engineering requires that we work in parallel on all aspects of design, fabrication, metrology and assembly, so the design in the end can be manufacturable," she says. "It alleviates some of the tension" that can crop up between different communities, she argues, "while forcing solutions that are truly innovative."

Pushing forward freeform design

It's a good thing the dialogue is healthy, as freeform-optics design tools, like those for fabrication, continue to advance. One area of improvement lies in the sheer speed of computers—obviously key to making freeform feasible at all and to its core fabrication technology, but also, arguably, even more important on the design side. "Of course, fabrication demands impressive CNC machines," says Forbes. "But the ultimate computer demands are generated in design, where, ideally, global optimization algorithms can play a key role in uncovering novel systems that can eventually become part of an engineer's intuition and toolbox."

Rogers likewise believes that among the most important design tools that have emerged recently are simply more efficient optimization algorithms. "That's really important, because of how computationally intensive freeform design is," he says. "You have to sample the field very densely, and directly optimize on the aberration coefficients, so you're doing a lot of work on each [computing] cycle. Having a more efficient optimizer really makes a difference."

Duerr, too, cites advances in computing power as a key development in freeform design's evolution, and believes that future advances, both in computing speed and particularly in areas such as machine learning, could extend the design frontiers. "You can think about computer algorithms where you try to come up with some good ideas for the starting design," he says, "and they are optimized to reach a final system." Yet Duerr stresses that computer power in itself isn't what's driving the freeform design train; instead, it's the demand for specific applications—particularly off-axis systems, where "you really need freeform to get the full potential of your design."

With respect to design tools and strategies, Duerr notes that things are "rather fragmented at this point" and that there isn't "one real state of the art." Many successful freeform design strategies start with a basic, well-constrained traditional design and optimize from there. Another "really promising approach," according to Duerr, is the nodal aberration theory pioneered in a 2014 *Optics Express* paper by Rolland and Thompson, in which known aberrations are used to come up with a recipe for controlling or cancelling them in the system design. Still evolving, he says, are "direct design" methods that attempt to directly calculate the system based on differential equations or numerical calculation of dense point clouds prior to any optimization.

Interestingly, one area in which Duerr believes freeform design tools might be lagging a bit is in their actual integration into the software packages that designers use in their day-to-day work. "The commercial optical design programs really need to catch up with the pace of development in freeform optics," he says, noting that freeform surfaces still are often more an "add on" than an integral part of these packages. "They're improving a lot," Duerr says, "but they need to go further."

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—*Gregory Forbes*

Metrology: Taming the elephant

At some point, both designers and fabricators of freeform optics run up against the old adage: You can't make what you can't measure. And all of the experts we spoke to cited metrology as *the* big issue in moving freeform forward. "Measuring large, fast, convex surface shapes, with millimeters or more of departure from the sphere, to nanometer accuracy is an enormous challenge," says Forbes. Rolland calls metrology "the elephant in the room"—though she adds that she's excited about the "steady progress" under way to solve the issue.

Traditionally, Rogers explains, the quality of spherical surfaces was measured using interferometry, but for aspheres and freeform surfaces "that's harder to do." One solution has been interferometers that use sub-aperture measurement, and the results of which are "stitched" into a larger interferogram used for the actual testing. But even stitched interferometry, or other, sophisticated approaches such as computer-generated holograms (CGHs), eventually reach a limit in the total slope that they can measure. That can send the designer back to the drawing board—another reason, says Rogers, that optical designers need to be in constant contact with their fabricators.

From the fabricator's point of view, despite a lot of progress, metrology "is still a gating item," according to Nelson. She cites progress not only in stitching interferometry but also in non-contact probe profilometry, deflectometry, and CGHs, and says that solutions do exist for a subset of freeforms to achieve fractional wave precision using high-resolution profilimeters and CGHs. The "universal go-to tool," however, is still the coordinate measuring machine (CMM), which Nelson says has limitations.

"Companies are doing what they can using CMMs, ordering CGHs if possible, doing system tests if possible—but there's still a gap that needs to be addressed to push the industry to higher precision," says Nelson. "The envelope of possible freeform surfaces to test is large, and a universal solution is extremely difficult to achieve."

Research frontiers

Not surprisingly, getting to that more universal metrology solution constitutes one key area in current freeform-optics research, according to Rolland—who, in July 2013, co-founded the Center for Freeform Optics. CeFO is a research consortium that includes the University of Rochester, the University of North Carolina, and 16 government and industrial partners (https://centerfreeformoptics.org/the-team/affiliate-members). On the metrology front in particular, says Rolland, CeFO is developing multiple approaches, including addressing across-the-board issues such as properly accounting for measurement noise in surface-shape estimates, scalability of the techniques in a variety of parameters, and accurate reconstruction of surface-sag departures from indirect methods such as wavefront measurements.

Other key research efforts under study at CeFO, Rolland says, include coming up with mathematical descriptions of freeform surfaces, to optimize design for manufacturing; getting a better view of the detailed optical aberrations of freeform surfaces;

working toward an ever-better science of freeform fabrication, to allow for "predictable, repeatable, and cost-effective" large-volume manufacturing; and even envisioning how freeform might fit into "the space of snap-together optics." Rolland notes that CeFO, which operates under a U.S. National Science Foundation award, focuses in particular on precompetitive research, and looks at questions across the supply chain, as well as at improving prospects for large-volume manufacturing "so freeform optics may in the future enter the consumer market."

" The freeform revolution is in its full ascension. "

—*Jannick Rolland*

From a design point of view, Duerr says there are a wide variety of important research questions on the table right now. He points in particular to three: How to provide a comprehensive, generic strategy that gives designers a structured approach to incorporating freeform surfaces; how to determine how many freeforms are really required in an optical design, and where to place them; and how to incorporate not only design performance, but also fabrication and assembly feasibility, directly into the design process. On the fabrication side, Nelson observes that metrology—and, more specifically, how to precisely locate features on the freeform surface with respect to other surfaces and coordinate systems—remains the biggest research question today. "Physical and possibly optical fiducials," she says, "are extremely important in the fabrication and eventual alignment of freeforms in systems."

Are we there yet?

Research on these and other questions, as well as the practical experience of fabricators and designers working on and with the tools, has already hugely advanced freeform optics in the past five years, and should continue to do so. "The freeform revolution is in its full ascension," says Rolland, pointing to the growth of CeFO from 7 members at its 2013 launch to 16 members today. Freeform, she says, is a "disruptive technology" that is "advancing on all fronts."

Duerr characterizes the revolution as being "at an intermediate state." Like Rolland, he sees progress across disciplines, and momentum continuing to build. "The originally envisioned revolution of an 'ultimate integration of computers with the end-to-end process of creating optical systems' is not there yet," Duerr says. "But all subdisciplines are working together toward such a scenario."

That kind of teamwork, according to Nelson, has been essential in putting freeform on a fast track. "Freeforms are often compared to what aspheres were 20 years ago," she notes, "but the community is on a much quicker learning curve, and will likely get there in half the time." She attributes that pace both to increased computing speed and to an ever-greater culture of collaboration. "We are already seeing freeforms implemented in designs today," says Nelson, "and in less than 10 years their use will be as common as an asphere."

And, says Forbes, the prospects of ongoing improvement and innovation in this space look effectively boundless. "Although [development] is presently surging, this has been ongoing for generations, and, because of ever-higher performance/cost goals, is sure to continue far into the future," he observes. "It's just one of the many reasons that optical scientists and engineers have enjoyed challenging jobs for centuries—and will long continue to do so!" OPN

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