AN OVERVIEW OF FREEFORM OPTICS PRODUCTION

Nelson E. Claytor, Donald M. Combs, Oscar M. Lechuga,
John J. Mader, Jay Udayasankaran

Fresnel Technologies, Inc., 101 W. Morningside Drive, Fort Worth, TX 76110

Abstract

The first widely used freeform optics formed part of the viewing optics of the Polaroid SX-70 camera in the early 1970s[1]. The molds for these optics were made through a painstaking, essentially manual process. Since then, advances in design, machining, control systems, and metrology have combined to make freeform optics production less laborious—but in many ways the field is still in its infancy. We will discuss the challenges in design, fabrication, metrology, and integration that we have encountered, in the context of various applications that have been found for freeform optics.

Since freeform optics are only now beginning to be widely used, there is not even universal agreement on what constitutes a freeform optic. For our purposes, we will define freeform optics as those optics that do not have rotational symmetry. We will include lens arrays among freeform optics, though they often are not included, since they point up many of the same fabrication, alignment and metrology problems posed by completely general freeform surfaces.

Freeform optics are useful in many different areas. Some of those we have encountered include computational imaging[2], compact projection displays, document security, curing of polymer dental filling material, controlled diffusers for lithography, microscopy, and many others. There are, however, many challenges that inhibit the more widespread use of freeform optics. The challenges fall into the categories of design, fabrication (including both direct fabrication and molding), metrology, and integration of freeform optics into systems. Integration into systems is a particularly difficult challenge, but can often be made easier through careful design of integrated mounting with the optics.

The design challenges are many. Probably the most basic is to understand when and where freeform optics can most effectively be used. While sometimes it is clear that, for instance, a lens array is necessary to make a system work, it is often not clear that a more general freeform surface can benefit the system's performance. In fact, even if it is evident that use of one or more freeform surfaces will benefit the system, it is not always clear where those surfaces should be placed. This is highly application dependent. For instance, the phase mask in a computation imaging system is generally placed at the aperture stop, but in some cases it may be preferable to place the phase mask elsewhere. In the case of a compact rear projection system, a freeform folding mirror was used in combination with a freeform corrector in front of the projection lens. The question that arises in this case is then how most efficiently to split the nonrotational component between the various surfaces.

Another design challenge lies in how to describe the surface, both to the design software and to the fabricator. An example of this is the freeform corrector mentioned above, which is shown in Figure 1. Questions arose during the design process of how much nonrotational "power" to put on this surface as compared to how much was placed on the folding mirror. Further questions arose of how the design could be communicated from the designer to us so that the lens could be fabricated. We wound transferring the design though communication of the sag at each of a relatively coarse grid of points. This method worked reasonably well for this application, but has some dangers, including the possibility that interpolation between the grid points will distort or fail to capture essential features of the design. This is particularly difficult given the current state of freeform metrology, since it is difficult to measure the entire surface at once and compare to the entire surface of the original design.

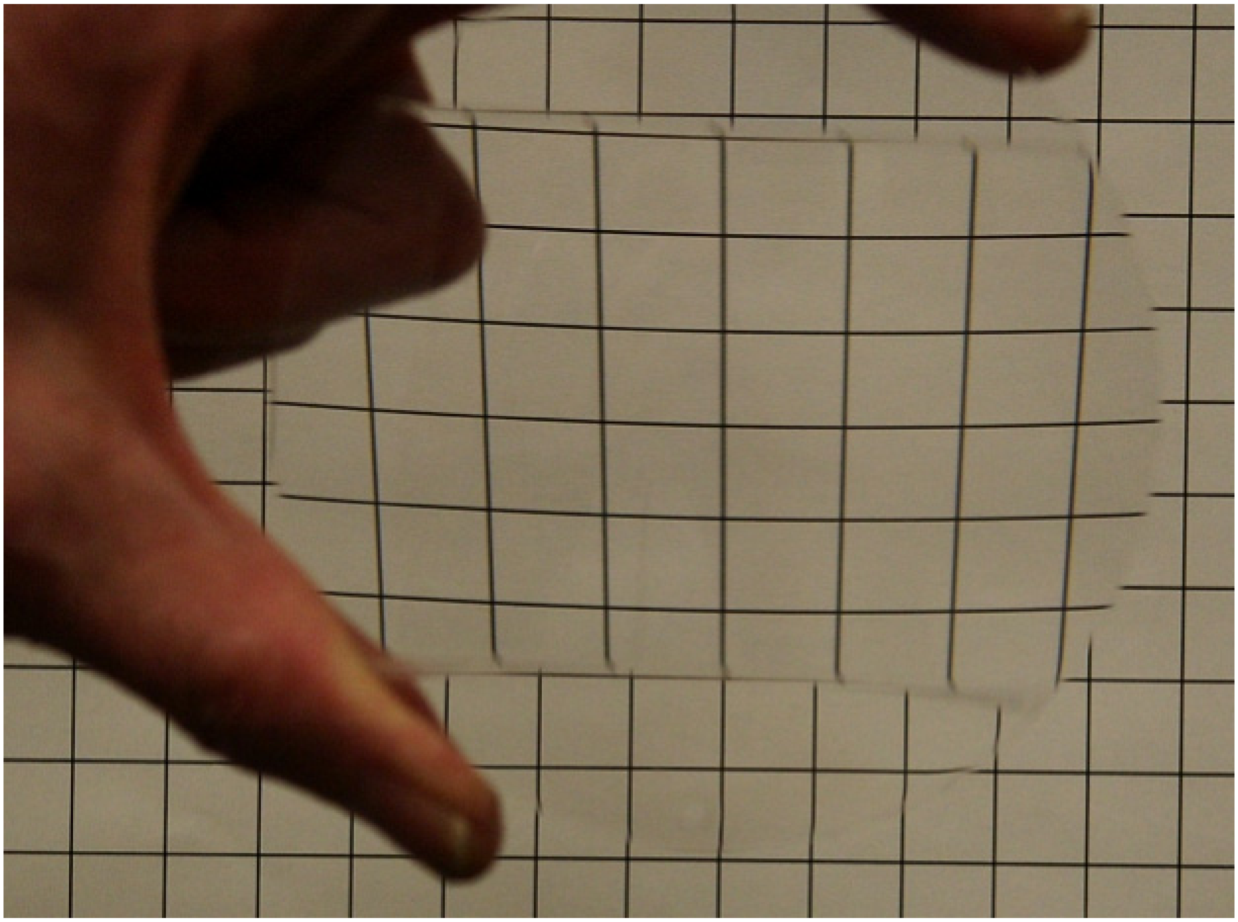

Figure 1. Freeform corrector used in a compact rear projection display system.

We also found during this project and others that tolerancing of freeform surfaces is not well understood. Both the designer and the fabricator are more or less working in the dark as to how much deviation from the desired surface can be tolerated. Poor understanding of the tolerances required for a given system, and especially the inability to determine whether looser tolerances will still provide the desired performance, tends to drive up the cost of freeform optical systems. Tolerancing also is closely linked to the metrology needs for a given system; for instance, it needs to be understood whether a metrology instrument with a given accuracy will adequately characterize the surface. It also needs to be understood with the scanning instruments that are primarily used today whether the sampling interval misses some essential component of the surface's geometry.

There are also many challenges in fabrication of freeform surfaces. We generally use four different methods for fabrication of freeform surfaces. Each of these methods can be used both to directly machine a freeform surface, for instance for prototyping or in materials such as germanium, and also can be used to machine a mold for the injection or compression molding of a freeform surface from plastic. These methods include fast tool servo; slow tool servo, also known as slow slide servo; flycutting; and milling. Others have used other methods, including abrasive grinding and lithography to make computer generated holograms. Grinding is necessary for certain processes, including the manufacture of carbide molds for molded glass freeforms and direct machining of steel mold inserts for injection molding of plastics parts.

Fast tool servo machining involves axial motion of the tool in coordination with the rotation of the spindle. Since the tool can be moved in coordination with the spindle, non-rotationally symmetric parts can be made on a lathe. This motion is usually accomplished by a piezoelectric actuator servoed to the spindle rotation. Since piezo actuators typically have only a small range of motion, between a few and about 200 μm, the range of deviation from rotation symmetry is also limited. The high stiffness and low moving mass of piezo actuators allows for high bandwidth in the control of the motion, which is a significant advantage of piezo-actuated systems for fabrication of non-rotationally symmetric optics. Mechanical amplification of the piezo's motion can be used to extend the range of motion, but this technique typically introduces significant loss of stiffness, as well as significant inaccuracies in the tool's motion. Our fast tool servo has a 180 μm total range of motion, as compared to the more typical 30 μm total range of motion. The bandwidth of our fast tool servo is about 150 Hz, while the bandwidth of many commercial fast tool servo systems can approach 1 kHz for very small deviations. The large range of motion of our fast tool servo allows us to fabricate a number of optics that cannot be fabricated with the many commercial systems, while the reasonable bandwidth and stiffness allows these optics to be fabricated with good surface finish.

An example of a part fabricated with the fast tool servo is shown in Figure 2. This is a cubic phase plate used in computational imaging. The negative of the shape of the phase plate was diamond machined with our fast tool servo in a nickel-plated stainless steel mold insert. This mold insert was then used to injection mold the part shown in Figure 2 from acrylic.

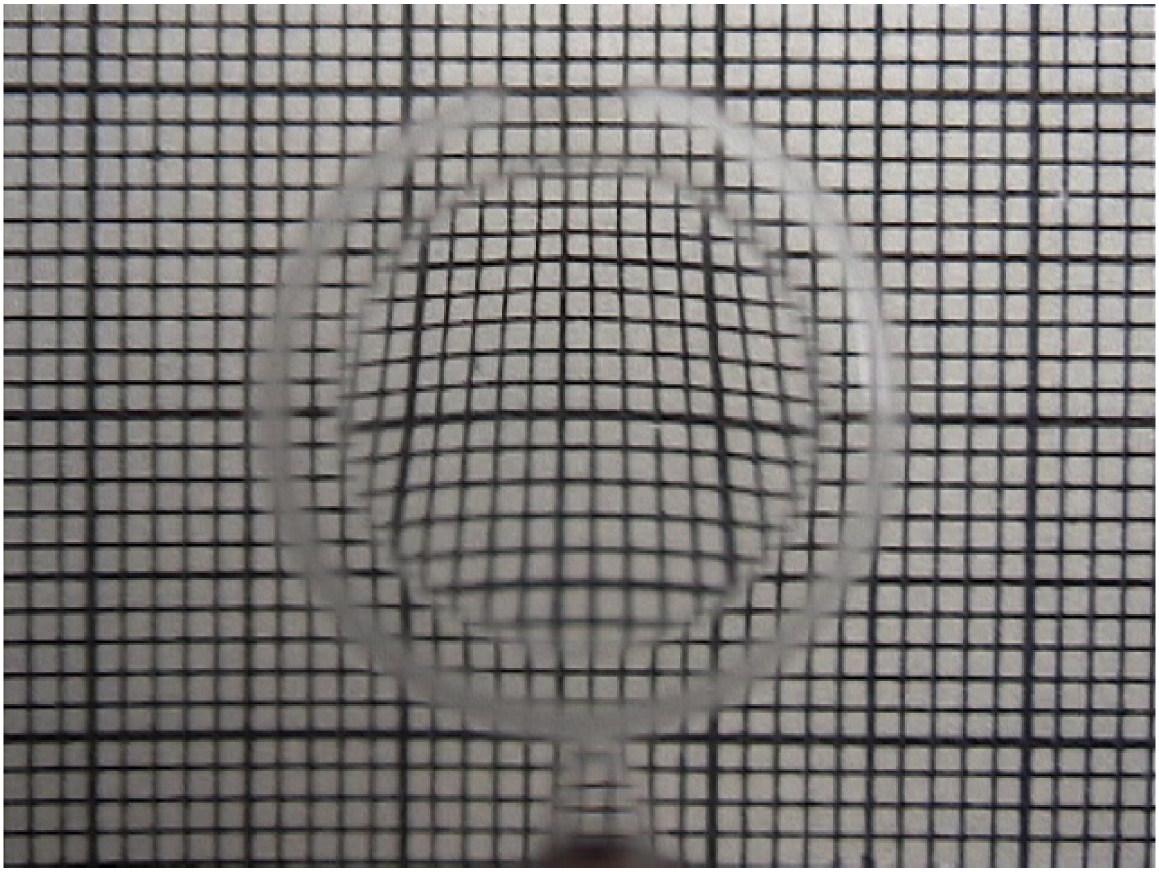

Figure 2. Injection molded cubic phase plate for computational imaging. Mold fabricated with fast tool servo diamond turning.

Another fabrication technique we have used is slow tool servo, also known as Slow Slide Servo. This technique also moves the tool in coordination with the rotation of the work spindle, but uses the machine's Z slide instead of a separate piezo actuator. The advantages of using slow tool servo instead of fast tool servo include the ability to fabricate parts with much larger deviations (millimeters) than would be possible with a piezo-actuated fast tool servo, as well as not having to purchase and integrate an additional, complex component. The biggest disadvantage of this technique is the low bandwidth that is available, typically only a few Hz because of the mass of the slide. This limits the cutting to slow spindle speeds, which can cause degradation of the surface finish relative to more normal spindle speeds of a few hundred RPM. The necessity for slow spindle speed can also lead to long cycle times. An example of fabrication using slow tool servo is shown in Figure 3.

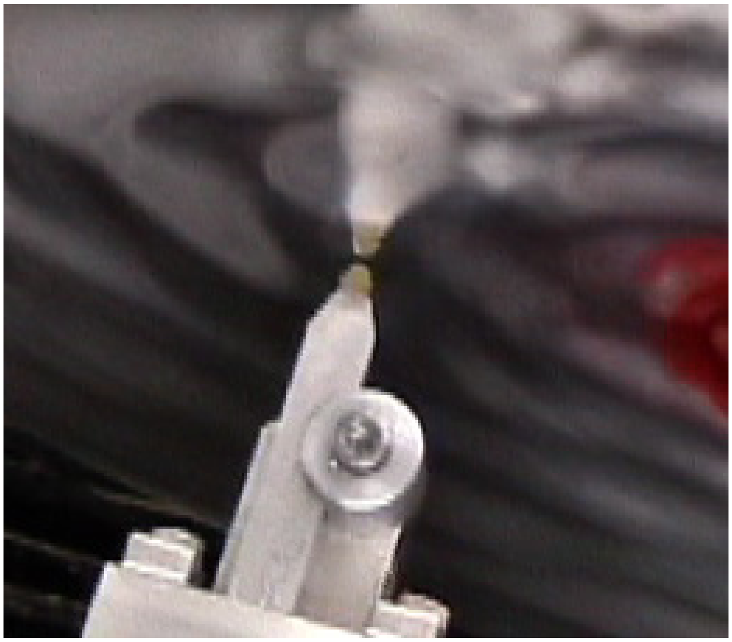

Figure 3. Slow tool servo cutting of the mold for a large lighting component. The tool moves in coordination with the spindle motion to trace out the "waves" on the surface.

The third and fourth fabrication methods—flycutting and milling—are closely related. The primary difference is in the shape of the tool; a flycutting tool has very different radii in the directions perpendicular and parallel to its rotation axis, whereas a milling tool is typically circular or nearly so. In both techniques, arbitrary shapes can be manufactured by tracing over the surface in any of a number of patterns—raster, spiral, offset, and so forth. Flycutting is typically used for open, nearly flat parts, while milling is typically used for steep parts and for lens arrays. An example lens array, compression molded from a milled mold, is shown in Figure 4. Each lenslet of this lens array has a very steep slope at its edge, approaching 70°. These lenslets cannot be measured using conventional techniques, which points up some of the metrology needs for freeform optics.

Finally, all of the above methods can be used to make molds for volume production of freeform optics in plastics materials, and in fact this has been the focus of our freeform optics efforts. The molds can be used for compression molding or for injection molding. Compression molding offers the advantages of very low molded-in stress and extraordinarily good replication of surface features, while injection molding offers the advantages of relatively easy molded-in alignment features and very inexpensive volume production. Compression mold tooling is generally less expensive, so compression molding can provide a good method to try out an idea if the geometry is suited to compression molding—that is, generally flat, without extensive mounting features.

The shape of the lenses in the lens array of Figure 4 is shown in Figure 5. A form Talysurf can measure slopes up to about 35° before the forces on the probe make it inaccurate, and a white light interferometer can measure slopes up to about 25° before too little light makes it back into the instrument to make a measurement. Clearly, neither of these instruments is adequate to measure the nearly 70° slope at the edge of these lenses. This is a particularly difficult situation because the edges are the most likely place for errors, both in generation of the mold and in molding. This object was measured and validated with a measuring microscope, laboriously traversing and refocusing the microscope to trace out a curve in two dimensions. This method is clearly not adequate for production, but neither is any other that we have so far found commercially available.

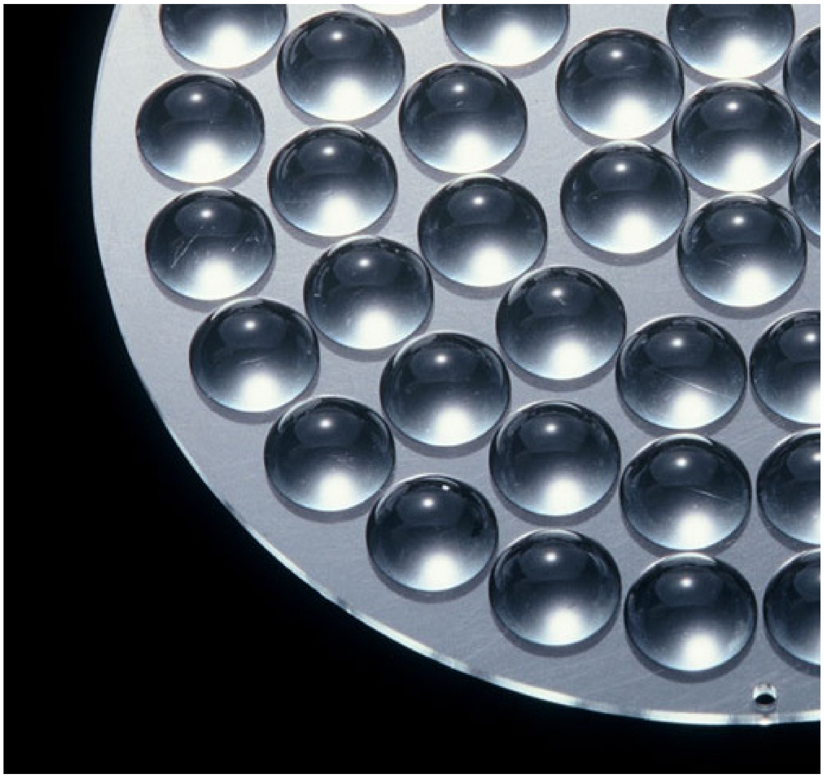

Figure 4. Array of 64 6 mm diameter, f/0.6 aspheres.

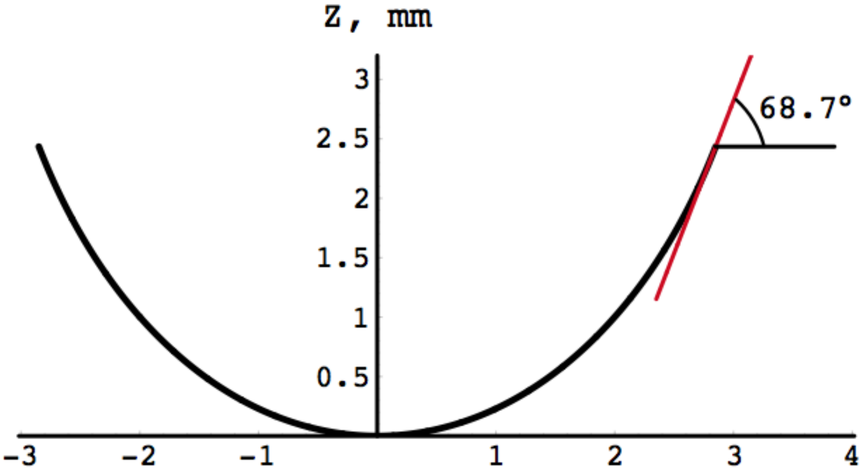

Figure 5. Shape of lenslets of array in Figure 4.

New metrology tools are clearly needed. The breadth of possible surface geometries points to the need for more than one type of tool, so that there is considerable room for innovation in this area. Both hardware and software tools are badly needed. Profilometry seems to us to be most likely to meet our needs, but the profilometer needs to be more sophisticated than the Form Talysurf, particularly in its software and hardware for 3D scanning measurements of surfaces. The optimum machine geometry, probe type, and software remain to be settled, and again, there is room for more than one of each.

We also find that integration of freeform optics into systems presents many challenges. The most successful methods of addressing these challenges so far involve features molded into the optics, so that once the geometry has been made correctly once in the mold, every piece molded takes advantage of that geometry. However, there are pitfalls even here, with mechanical stresses and with the possibility of designing a part that is very difficult to mold.

In sum, the challenges facing mainstream acceptance of freeform optics are significant, and the tools are in many ways in their infancy—but these are really interesting optics!

References

1) W.T. Plummer, J.J. Mader, J.W. Roblee, and J. Van Tassell, "Precision Engineering at Polaroid", Proceedings of the 8th International Precision Engineering Seminar, Compiégne, France (1995)

2) "Reducing Complexity in Computational Imaging Systems," Optics Express, Vol. 11, No. 18 - September 8, 2003 pp.2102-2108 Kenneth Kubala, Edward Dowski, and W. Thomas Cathey. Many other publications on the topic by authors at CDM Optics are available at http://www.cdm-optics.com/site/publications.php.