Freeform and conformal optical manufacturing
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ABSTRACT
Future optical systems are moving away from traditional spherical optics. The anticipated benefits are numerous for freeform optics as they provide better aerodynamic characteristics for aircraft, lighter weight for space missions, and smaller size for medical procedures.

Currently the design and utilization of conformal and freeform shapes are costly due to the difficulties introduced with fabrication and metrology of these parts. Techniques for creating these complex optical surfaces are still in development for traditional optical materials. OptiPro has a unique opportunity create manufacturing solutions through computer controlled multi-axis optical generating, polishing, and metrology machines. OptiPro Systems is continuing to develop advanced optical manufacturing technologies. OptiPro has made toric and freeform arch shapes. OptiPro’s existing manufacturing platforms include its eSX grinding, UltraForm Finishing, and UltraSurf non-contact surface scanning system, which will be used for grinding, polishing, and measuring conformal and freeform shapes.

Freeform surfaces are initially generated using deterministic micro-grinding with diamond bonded tools. Tool paths with up to five axes of simultaneous motion are required to generate and polish the optical figure of conformal surfaces. Sub-aperture corrective polishing will need to vary the amount of time the tool contacts at each location in order to remove the proper amount of material. These locations and dwell times are derived from a surface figure error map provided by OptiPro’s UltraSurf. Research and development of the freeform manufacturing process will be presented.
1. INTRODUCTION

1.1 Freeform and conformal surfaces

From a manufacturer’s perspective, freeform optical surfaces are shapes that are not manufactured by standard spherical or aspheric manufacturing techniques. They can include a wide range of geometries and can usually be broken down into the following sub-classes; off-axis sections of rotationally symmetric shapes, rotationally symmetric non-standard shapes, shapes that conform to the platform where they reside (i.e. conformal), and complete freeform.

Conformal shapes may or may not have rotational symmetry. Some examples include automotive optics and headlights, and optics on the body of aerodynamic surfaces of airplanes and unmanned aerial vehicles (Figure 1). In both of these cases, the goal would be to reduce the effects of drag for better performance, but still maintain proper optical characteristics. Complete freeform shapes have no central definition. They are frequently defined by complex mathematical equations, point clouds, splines, or computer aided design (CAD) files. Communication of the desired surface from the optical designer to the manufacturer can be challenging.

Figure 1: Freeform and conformal shape for automotive application

1.2 Micro-grinding

Complex optical shapes require raster grinding techniques (Figure 2a). These techniques usually require three to five axes of simultaneous motion to maintain tool orientation during the grinding cycle. The simultaneous motion is provided by a computer numerically controller (CNC). Typically you would use a spherical shaped diamond grinding wheel, similar to the tool used in grinding asphere optics (Figure 2b). The deterministic micro-grinding techniques that made precision asphere manufacturing possible are being employed by OptiPro. Surface metrology from a coordinate measuring machine and OptiPro’s UltraSurf is used to provide a form error map. The form error map can be used to compensate for tool wear and machine alignment, allowing us to grind freeform optical surfaces accurately for the final polishing step.
UltraForm Finishing (UFF) is a sub-aperture polishing process that has been developed by OptiPro systems to polish spherical, aspheric, and free form surface geometries. It is a CNC deterministic process that uses surface metrology with a measured removal function to generate a tool path (Figure 3b). This path will move the UltraForm polishing wheel (Figure 3a) along the optical surface in a controlled manner to reduce the form error. The wheel consists of a compliant material and can be manufactured to various diameters and hardnesses. Wrapped on the outside of the wheel is a belt of polishing material. The belt may be bound with abrasive materials such as cerium oxide and diamond, or made of a polyurethane material traditionally used in optical polishing. A combination wheel diameter and hardness with the assortment of belts allows the operator to control the shape and depth of the removal function.

A free form optic can take any shape, and may not be rotationally symmetric. These types of surfaces may have no simple mathematical definition. To be able to keep a constant removal function during UFF processing, the UltraForm wheel will need to be kept tangent to the surface. This will require 5-axis of simultaneous motion. OptiPro is developing an interface to integrate freeform geometry, surface error maps, and tool geometry to polish freeform shapes to optical tolerances.
1.4 UltraSurf

OptiPro Systems has been developing the UltraSurf, a non-contact measuring system using state of the art, air-bearing, precision motion control (Figure 4). OptiPro has demonstrated UltraSurf’s measurement capabilities on industry standard optical surfaces such as spheres and aspheres. The five-axis, non-contact single point measurement is flexible enough to handle common metrology problems such as surface roughness, slope error, and high departure from base radius.

UltraSurf measures with sub-micrometer non-contact point sensors to collect surface information. Various sensors are commercially available from multiple companies, each with their own distinct optical measuring technology. One optical sensor uses white light confocal chromatic imaging to measure individual optical surfaces. Another optical sensor uses low-coherence interferometry with a near infrared laser, and is able to measure the inside, outside, and thickness of optical materials at a single point.

UltraSurf scans an optical sensor over the surface of the part under test, keeping it normal to the surface (Figure 5). The single point measuring method coupled with computer-controlled motion gives the UltraSurf flexibility to measure greatly diverse geometries. Ultimately, a three-dimensional point cloud of the measured surface is generated. The cloud is compared against the desired shape to calculate deviation and various surface parameters.

Figure 4: UltraSurf axes of motion, three linear (X,Y,Z) and two rotary axes (B,C)

Figure 5: UltraSurf measurement of conformal arch, fine ground surface
2. METHODOLOGY

2.1 Basic Process Flow

The process OptiPro uses for processing complex shapes is as follows. The term “processing” will be used to mean either grinding or polishing.

1. Input part definition into processing software via CAD, equation, or point cloud.
2. Generate a tool path for the specific process
3. Process the surface on CNC equipment
4. Measure the surface on a CMM, UltraSurf, or other metrology
5. Input the form error calculated from metrology into the processing software
6. Generate a new tool path that will reduce the form error
   a. Grind correction adjusts the location of the tool at each step of the tool path
   b. Polishing correction adjusts the dwell time at each step of the tool path
7. Iterate steps 3 to 6 until form error has reached acceptable values

3. PROCESSING

3.1 Aerodynamic conformal dome

A common shape for aerodynamic domes is called an ogive. The processing and measuring is very difficult due to the high aspect ratio. The ogive is a type of conformal shape. OptiPro has been developing a process to manufacture the domes from their molded blank to final form.

Typically the domes are molded from a ceramic material to near net shape. In particular, OptiPro is working with a polycrystalline alumina that has similar mechanical properties as single crystal sapphire. The molded blank is ground using the UFF with a rough abrasive diamond belt. The long belt allows for longer tool life and the large contact area provides faster material removal when compared to a standard diamond grinding tool.

![Figure 6: Grinding the conformal ogive dome using UFF and a rough diamond belt, note large depth of cut](image)

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Polishing begins when the basic ogive form has been ground to near final shape. Polycrystalline alumina is a very hard material, so diamond polishing slurry is required. An abrasive belt with a spray-on diamond slurry is used reduce the surface roughness and form error (Figure 7). UltraSurf feedback is critical in this phase to get the most accurate estimate of the form error. The error map from UltraSurf (Figure 8) is fed back into the UFF dwell time algorithm to correct the irregularity.

Figure 7: Polishing the convex side of the conformal ogive dome with UFF and a diamond slurry

Figure 8: Ogive figure error before correction, unwrapped view on the left, PV: 8.4 um, RMS: 1.89 um
Iterating the polishing process with UltraSurf data allows for the surface to converge to the final specification. An image of the ogive after a polishing iteration is shown in Figure 9. The large bumps on the upper and lower edge have been reduced in magnitude. The peak to valley and root mean squared error was cut in half between the initial surface in Figure 8 and the subsequently polished surface in Figure 9. The final polished surface of the dome is shown in Figure 10. The material scatters visible light, giving it a cloudy appearance when polished. The OptiPro logo is clearly visible though both sides of the dome.

![Figure 9: Ogive figure error after correction run, unwrapped view on the left, PV: 4.15 um, RMS: 0.52 um](image)

![Figure 10: Final ogive dome, polished on both sides](image)

### 3.2 Freeform arch

OptiPro is working to create a freeform arch to optical tolerances. The arch is defined by a polynomial equation that varies the shape in the two principal directions. It cannot be polished by rotating the optic in the same fashion as the
ogive dome. A diamond bonded grinding tool is used on OptiPro’s eSX platform to shape the arch (Figure 11). Multiple axes of motion are used depending on the type of tool (e.g., ball, torus, bull nose, and wheel) and the surface of the arch (e.g., convex, concave).

Polishing the surface of the arch requires a more complicated tool path than grinding. Polishing must incorporate up to five simultaneous axes of motion. Also, the amount of dwell time at each location must be controlled to either remove material uniformly, or non-uniformly to perform figure correction.

Five axis motion is complex and may require different part orientations. The convex side of the arch was polished in a horizontal mode (Figure 12a). This orientation was used to minimize axis reversals that can occur when the five axis math breaks down. The concave side was polished in a vertical mode (Figure 12b), using four axes of motion. This mode does not have axis reversals and provided a safe method for get inside the narrow concave side.

Results from a few polishing iterations are shown in Figure 13. Initial grinding of the arch left residual lines in the part. UFF polishing significantly reduced the lines, as well as the low order error from the grind. Low order error is
induced by part misalignment on the machine. The final peak to valley and root mean square error was improved by a factor of five from the starting value. The final arch is shown in Figure 14.

![Figure 13: Arch before, PV: 25.5 um, RMS:3.97 um (left) and after PV: 3.94 um, RMS:0.53 um (right) polishing and correction](image)

![Figure 14: Final conformal arch, polished on both sides](image)

**4. CONCLUSIONS**

Freeform optics have the potential to revolutionize the precision optics industry. Advancements in manufacturing technology have allowed us to begin to create optical shapes that were never thought possible. As we move forward, collaboration between optical design and manufacturing will be required to facilitate a successful implementation of freeform optical systems. Advances in metrology will greatly drive the freeform metrology manufacturing, and current technology is able to push freeforms to near optical tolerances. OptiPro is continuing to explore developing new technologies and refining existing ones to further manufacturing capabilities.