SANDIA REPORT

SAND2007-0127
Unlimited Release
Printed January 2007

Design and Manufacturing of Complex Optics: The Dragonfly Eye Optic

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National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Abstract

The "Design and Manufacturing of Complex Optics" LDRD sought to develop new advanced methods for the design and manufacturing of very complex optical systems. The project team developed methods for including manufacturability into optical designs and also researched extensions of manufacturing techniques to meet the challenging needs of aspherical, 3D, multi-level lenslet arrays on non-planar surfaces. In order to confirm the applicability of the developed techniques, the team chose the Dragonfly Eye optic as a testbed. This optic has arrays of aspherical micro-lenslets on both the exterior and the interior of a 4mm diameter hemispherical shell. Manufacturing of the dragonfly eye required new methods of plunge milling aspherical optics and the development of a method to create the milling tools using focused ion beam milling. The team showed the ability to create aspherical concave milling tools which will have great significance to the optical industry. A prototype dragonfly eye exterior was created during the research, and the methods of including manufacturability in the optical design process were shown to be successful as well.

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FIGURES

1. INTRODUCTION

Sandia National Laboratories designed a novel, multi-layer, compound optic providing a wide field of view in a highly compact package and based on the eye of a dragonfly. The design consists of an array of 660um diameter convex aspherical lenslets arrayed around the outer surface of a 2mm radius hemispherical shell. These lenslets are aligned with an equal number of spherical concave lenslets on the inside of the shell. The shell is positioned on a smaller hemispherical shell and the lenslet pairs are aligned with tapered conical holes that prevent crosstalk between the optical pathways. This shell is in turn positioned on the end of a spherically ground bundle of fiber optics which transmit light signals to a detector unit. The optical assembly enables an entire system for horizon to horizon (~2π steradian) viewing in a cube of less than 5mm on a side. This small size is compared to previous attempts which have yielded either very large structures [1] or planar structures of similar size to the proposed dragonfly eye array, but exhibiting significant performance limitations due to the planar nature of the structure [2].

The manufacture of this multi-layer compound optic has presented many challenges including the creation of convex, aspherical micro optics, the alignment of the lenslets on the inside and outside of the hemispherical shell, the creation and alignment of the tapered conical holes, and assembly of the entire package. The creation of the outer hemispherical shell and its lenslets has required 5 axis motion in the diamond turning machine and the development of a means of precisely aligning the part to position the internal lenslets with respect to the external lenslets. This positioning, which would be fairly routine on a flat array, turned out to be quite challenging on the small interior of the hemispherical shell with tool clearance presenting significant challenges. A fixture was designed that leveraged the LVDT probing capabilities of the machine for alignment and part clocking. The creation of the convex, aspherical lenslets on the exterior of the shell also presented significant challenges. The challenges of creating these lenslets on the curved exterior of the shell will be described. The authors will present the challenges and the methods utilized to produce this component along with analysis of the optics produced.

1.1. Scope

This document includes many aspects of the design and manufacturing of the dragonfly eye optic. The text also pursues some of the important spinoff processes developed during the course of this research project including the Focused Ion Beam modification of diamond tools and the development of an interferometric system for the measurement of mesoscale optical arrays.

2. THE DRAGONFLY EYE OPTIC – DESIGN

One of the overarching goals of the project was to develop a strong partnership between the optical designers and the manufacturing engineers. This partnership included the need to create a method of communicating effectively and translating between optical design requirements and manufacturing requirements. The effort included helping the designers to understand what requirements could be made of the manufacturing processes and also helping the manufacturing engineers to understand the needs of the optical designers such that new processes could be developed to meet those needs. To promote all of this communication in the context of a real optical system with real requirements (and significant challenges), the Dragonfly Eye was proposed as a test subject.

2.1. Design Goals

The dragonfly eye optic is a complex, multi-layer optical array with significant design and manufacturing challenges. The optical system is designed to have nearly 2pi steradian field of view and the incoming images are portioned in such a way as to reduce image processing requirements to a minimum.

The proposed test bed optical system, emulating a dragonfly's eye, will be configured similarly to the optical array shown in Figure 1. The optic is designed as a wide field-of-view optical array for use in very small robotics. The proposed optic consists of 3.4mm radius hemispherical polymer shell with aspherical optics on the outer surface precisely aligned with aspherical refractive optics on the inner surface. This outer hemisphere is concentric to an inner hemispherical "sizing shell" that removes stray incoming rays and prevents crosstalk between the optical paths in the array. The light is then incident on the hemispherically polished end of an encapsulated fiber optic bundle that transfers the light from its hemispherical wavefront to a planar CCD array for data collection.

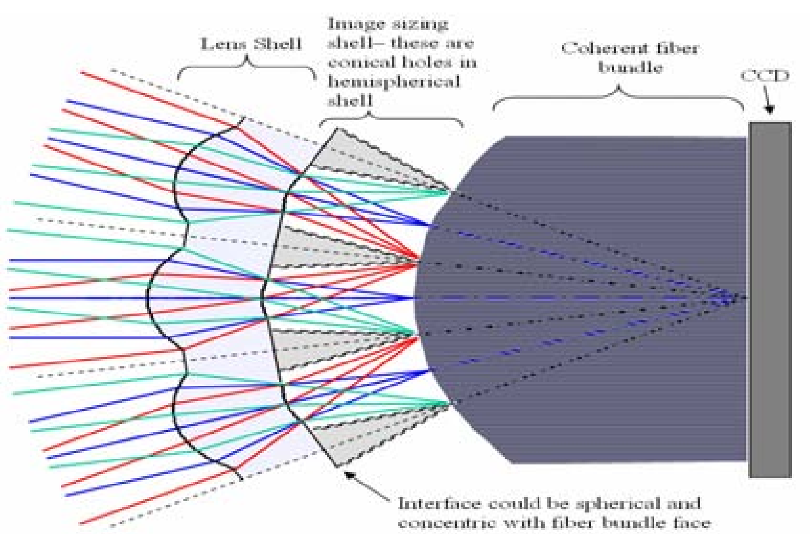

Figure 1. The Optical Array Representing a Dragonfly Eye Was Used As a Testbed

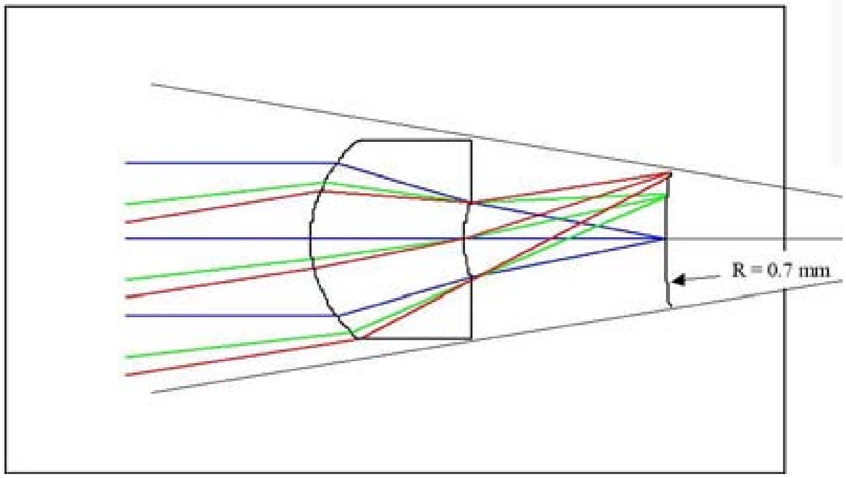

Figure 2. A Single Optical Column (Ommatidium) Extracted from the Hemispherical Array

The significance of the dragonfly eye becomes evident when ray traces are studied more carefully. Figure 2 shows a single optical column (ommatidium) extracted from the hemispherical array. This figure shows that the rays of light form an inverted image on the 2mm radius hemispherical surface of the fiber bundle. The spacing of the ommatidium can be chosen such that the image has overlapping data with surrounding ommatidia, or such that the data is imaged at only one location. The overlapping option was chosen for this design which provides a full image with no loss of data. Simple software could be utilized to overlap the redundant pixels to create a full image for the further processing. The compound eye structure is especially adept at tracking movement, which is represented as an object moving from pixel to pixel if moving perpendicularly to the optical axis, or as appearing in an increasing number of pixels if coming toward the optic. The array of optics around the hemisphere allows the optic to have a wide field of view (>150º) while allowing the optic to remain stationary without the need to rotate and track objects.

This optical system is ideally suited for meso and micro-robotic applications where the size of the optic is limited, the volume and power of image processing are limited, and the minimum number of moving parts is desired. For this application, the target size of this optical system will be a 3.5mm radius hemisphere. This puts the dimensions into the mesoscale with some features on both the micrometer and nanometer level and all tolerances under 3µm. This makes the optic much more valuable to designers of micro robotics and miniature sensors than previous large-scale solutions.

2.2. Optical Design

As with most engineering design, optical engineering (OE) is done with intuition and some computer support. Lens design codes are quite mature. They can quickly find the optimal design in the design space specified using (i.e.) a damped least-squares criteria. The code used most frequently here at Sandia is "Zemax". It allows one to optimize aspheric surfaces, cylindrical and other surfaces of rotation, diffractive elements, tilts and displacements in the presence of constraints on first-order optical properties, lengths, shape constraints, multiple wavelengths, multi-configurations (like zoom lenses), and more.

The Dragonfly lens was designed roughly as follows: A sketch of a group of lenses revealed what lens diameters and lengths would fit into a 7-mm diameter dragonfly eye. Other calculations were run to determine a logical resolution for a reasonable CCD detector and the minimum microlens diameter. The field of view of each lens was calculated from the system sketch. Finally, the lens for one lens column was postulated to be a thick lens with two aspheric surfaces. Finally, we assumed that any potential robot engineer customers would want the system to work in sunlight or the equivalent. With only one lens, white light operation requires a diffractive element to compensate for the dispersion of the plastic (or glass) lens. Finally, with the proper field of view and entrance pupil specified, along with the length constraints, the radii, aspheric components, and the diffractive surface were all chosen Zemax to optimize the image quality.

With a design in hand that was buildable and seemed to make sense, we reviewed the design with a team member representing potential applications of the technology. He was delighted, but then as we discussed the design and what would be hard (the diffractive element), he said that the first use for the system that he envisioned was as a robot mapper with a laser source. It was immediately obvious that we should not add the diffractive element until later—for a laser application, the dispersion of a plastic lens would not matter. Therefore, we reoptimized the lens without the diffractive element using only at the laser wavelength.

A second mid-course correction was done to correct for the radius of the diamond provided by the manufacturer when it did not match the design closely. Knowing this, the previously designed lens was inspected and a tool radius similar to its concave radius was selected. Then the lens was redesigned with this fixed radius. We had added some new variables to achieve decent image quality. We varied the front surface, the lens thickness and the overall Dragonfly lens' footprint (previously fixed).

2.3. Optical Design Specifics

Each optical sub-system (ommatidium) can cover slightly more than a 20^o field of view, thus ~60 ommatidium in a hexagonal array are required to cover approximately a cone angle of 150^o. The coherent fiber bundle (meaning that the fibers are parallel to one-another) is 4mm in diameter and the fibers are 12µm in diameter. The front face of the fiber array is ground and polished to a 2mm radius. The values given for the fiber bundle describe the first prototype and could vary significantly in future designs. The 1.) field of view of 20^o, 2.) the 2mm front radius of the fiber bundle, 3.) the requirement that the optics don't interfere with one-another specifies and 4.) the minimum required resolution for the fiber bundle completely specify the first order optical properties of each ommatidium. The field of view and the radius of the fiber bundle set the focal length of the ommatidia. The spacing between adjacent ommatidia specifies the maximum diameter of the collecting apertures.

The maximum collecting aperture, focal length, and 1.06µm wavelength (for the first prototype) set the maximum system resolution. The focal length is 1.38mm and each ommatidium's entrance pupil is 650µm so the whole system can fit inside a 7mm diameter sphere. The shape of the two surfaces of the 0.62mm-thick lens defining each ommatidium can be chosen to maximize the image quality across the $\pm 10^o$ field of view. Allowing the surfaces to be aspheric gives a design where the minimum RMS blur size varies between 3.5µm and 10µm with a 6µm average.

This range of spot sizes fits comfortably on the 12μm fiber ends. Note that one of the hardest requirements in the design was to force the image plane to conform to the convex face of the fiber bundle.

3. THE DRAGONFLY EYE OPTIC – MANUFACTURING

The dragonfly eye optic was selected as a capability demonstration because the manufacturing of this optic is very difficult. The design includes matching pairs of spheres and aspheres arrayed around the surface of a hemispherical shell. To compound the difficulty, the convex lenslets are aspheres and diamond tool manufacturers do not have a means for creating concave diamond mills that are aspherical (noting that concave mills produce convex optics). The project team addressed all of these difficulties, choosing and developing the manufacturing processes to achieve the highest quality optics possible. The selected processing method, the development of new capabilities, and the results of these processes are included along with thoughts regarding error sources and possible improvements which were not possible in the available timeframe.

3.1. Manufacturing the Lenslets – Turning vs. Milling

When fabricating aspherical optics, it is generally best if the optics can be produced by turning them on-center using a diamond turning machine. This utilizes the very high stiffness of the diamond turning machine and the high precision control of the axes to create the form of the optic. In turning on-center, the optic to be turned is centered on the spindle chuck, and a diamond tool is moved across the part in two axes. When machining an array, the part must then be repositioned such that a new lenslet is located at the center of rotation of the spindle, and the part can then be turned. When creating an array, this method gives the best possible form accuracy for each optic, but this comes at the cost of sharply reduced positional accuracy and it is time-consuming. Generally the method of repositioning the part is much lower accuracy than that of the machine axes and, if large enough, the repositioned part can require counterbalancing to achieve the desired surface finish. A metrology artifact turned in this manner is shown in Figure 3. The part is shown on the chuck for turning of the center optic in Figure 3(A) and shown in the offset position for the turning of one of the radial optics in Figure 3(B). Note the counterbalance that was added to the fixture for the machining of the non-centered optics.

The Dragonfly Eye optic would be quite difficult to machine using on-center machining because of the hemisphere on which the lenslets are to be machined. Instead of being able to simply move the part on a plane as was possible with the metrology target shown in Figure 3, the dragonfly eye requires that the hemisphere be rotated around the sphere's center as is shown in Figure 4. So, for each lenslet, both the azimuth and the elevation of the part fixture would have to be changed. Any changes to the fixture's center of gravity would have to be compensated by the radial adjustment of weights, and the fixture would have to position each of the lenslets to less than 1μm in each direction. Compounding this difficulty would be the need to reposition the optic for the machining of the interior lenslets with the same accuracy.

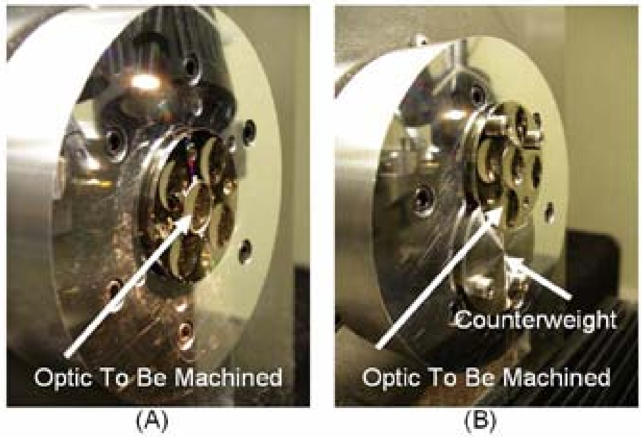

Figure 3. Metrology Artifact During On-Center Machining. (A) Shows the Machining of the Center Optic and (B) Shows The Machining of an Edge Optic Using a Counterweight.

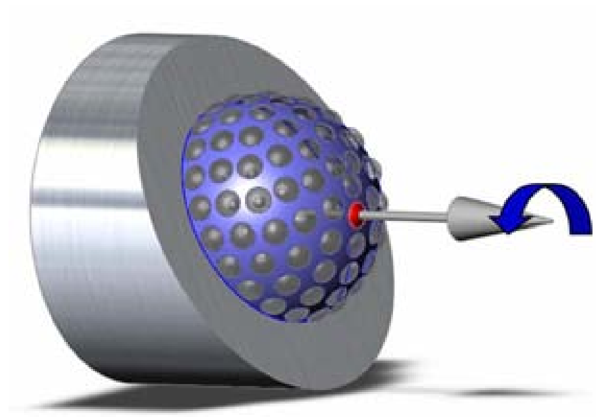

Figure 4. On-Center Machining of the Dragonfly Eye Would Require the Part to be Repositioned in Both Axis and Elevation for the Machining of Each Lenslet

Because of the need for highly repeatable positioning and alignment of the inner and outer lenslets for turning the lenslets on-center, the team decided to investigate alternative methods for fabricating the dragonfly eye optical system. An alternative to on-center turning is to diamond mill the optics. In this method, shown in Figure 5, the part is kept stationary while spinning a diamond mill plunges into the surface. The diamond mill has a concave cutting edge which creates a convex lenslet on the surface of the hemisphere. Once an optic has been completed, the part is rotated in azimuth to the next lenslet location using the positionable spindle (C Axis). If the milling spindle is mounted on an indexing table, the elevation can be changed and thus all lenslets can be machined. The most significant challenge of diamond milling is that the mill must contain a convex aspheric cutting edge which the diamond tool manufacturers are not able to create. Despite this challenge, the team selected the diamond milling method was chosen because of the anticipated increase in positioning repeatability.

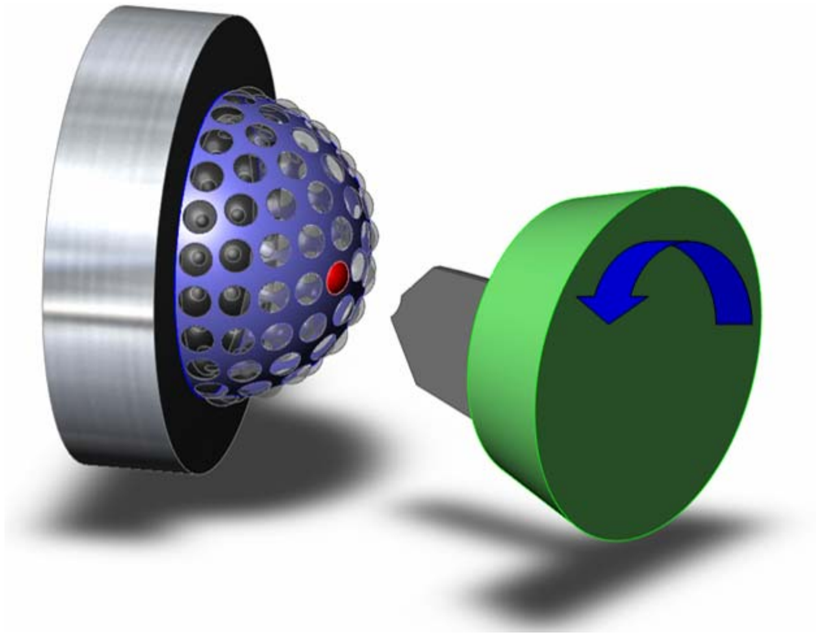

Figure 5. Diamond Milling Utilizes the High Repeatability Aspects of Diamond Turning, but Incurs Some Degradation in Optical Form in Exchange. In This Method, the Mill (green) Rotates While the Part Stays Stationary.

3.2. The Diamond Milling Process

A high speed grinding spindle was mounted on top of the rotary table and aligned with the axes of the machine tool so that its axis of rotation was coaxial to the spindle axis when the rotary table was positioned at 90 degrees elevation (the pole of the hemisphere). The spindle is shown as mounted on the indexing table in Figure 6 and a close-up view of the tool is shown in Figure 7.

The diamond milling method is especially attractive because the C-axis has a positioning repeatability of ±0.5 arcseconds and the indexing table has a positioning repeatability of ±0.3 arcseconds. (This gives a lens centration of ~20nm or $\lambda/50$ which is excellent from the opticer's point of view.) This is a particularly good application of these axial positioning units as the accuracy of each, while good at ±12 arcseconds for the C axis and ±1.5 arcseconds for the indexing table, is no where as good as the repeatability. The machining of the lenslets requires that the outer lenslets be milled, the hemisphere flipped and the interior lenslets machined. Because the lenslet switches from one side of the spindle rotational spindle to the other, the indexing table is positioned at the same position for the matching interior and exterior lenslets as the interior lenslets are machined on the opposite side of center as the exterior lenslets. This can be seen in Figure 8 where the milling spindle is at the same angle for the corresponding inner and outer lenslets.

Figure 6. The Aspheric Diamond Mill Is Shown In the Collet of the High Speed Spindle Which Is Mounted on a Highly Repeatable Indexing Table and Positioned on the Z Axis of the Diamond Turning Machine

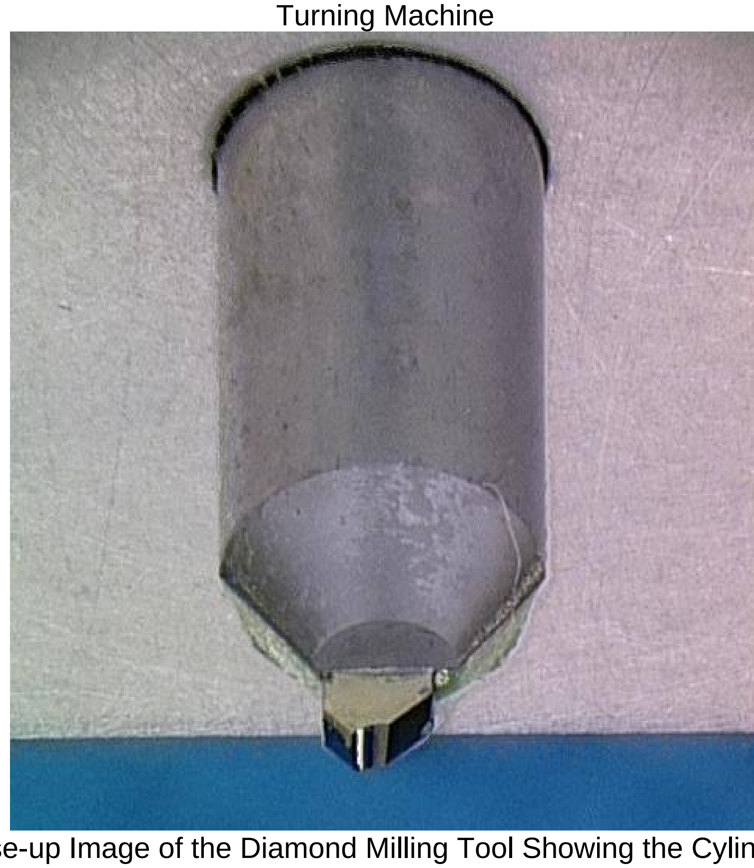

Figure 7. A Close-up Image of the Diamond Milling Tool Showing the Cylindrical Relief Angle Cut Into the Tool Below the Tool's Cutting Edge. The Tool Shank Is 3.1mm.

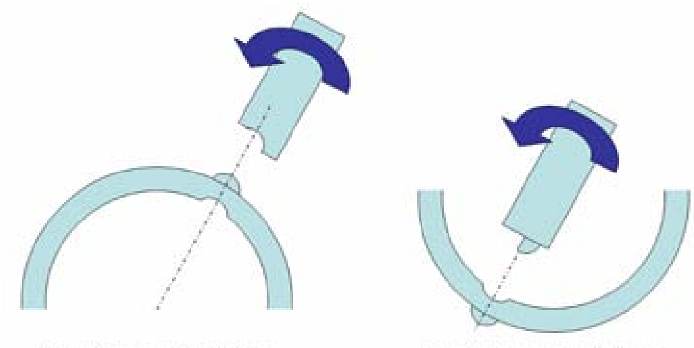

Figure 8. The Corresponding Exterior (left) and Interior (right) Lenslets Are Milled With the Milling Spindle Positioned At The Same Angle on the Indexing Table

3.3. Fixturing the Dragonfly Eye Optic

The need for good repeatability between the interior and exterior lenslets dictated the utilization of fixturing that would accurately locate the part for both sets of lenslet machining. The fixturing required that the center location of the optic be repeatable and that the rotational (azimuth) angle be repeated with high accuracy. To achieve this requirement, a fixture was devised that leveraged the repeatable positioning of round parts with the height measurement capability of a Linear Variable Differential Transformer (LVDT) that is a feature of the machine. This feature, called the Workpiece Error Compensation (WEC) Probe, is generally used to measure axisymetric optics that have been diamond turned. The geometry measurements are normally used to correct a part program to compensate for tool radius errors, centering errors, and geometric definition errors. For this application, however, the WEC probe was used to find the high point on a set of spheres.

The WEC system, shown in Figure 9, consists of an air bearing LVDT with a precision ruby sphere on the tip. The probe mounts on a 3-ball kinematic mount in the machine for repeatable location of the probe. For this application, the hemispherical part was determined to be too difficult to handle on its own, so the hemisphere was machined from a larger cylindrical acrylic disk. First, two holes are drilled into the disk approximately 180° apart. Secondly, the part is faced on both sides so that the sides are flat and parallel. Next, the outer surface of the hemisphere and the OD of the disk are machined in the same setup so that the centers are highly concentric. Lastly, the part azimuth is set using two precision steel spheres which have been glued into the two holes in the disk. The fixturing assembly is shown in Figure 10. It is important to note that the two precision spheres protrude from both sides of the disk and that the acrylic disk is held to the machine spindle's vacuum chuck on a porous carbon disk that contains clearance areas for the alignment spheres.

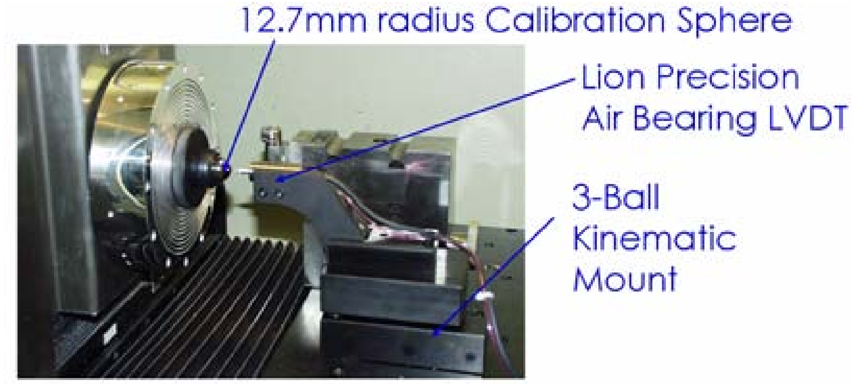

Figure 9. Workpiece Error Correction (WEC) Probe Showing LVDT During Calibration on a Precision Sphere

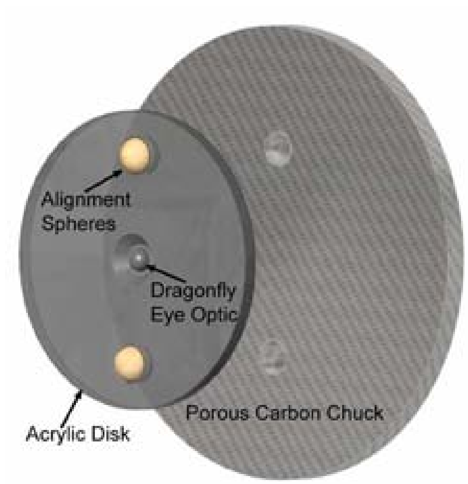

Figure 10. Fixturing Method Developed to Repeatably Locate the DragonflyEye Optic for Machining on the Interior and Exterior of the Hemispherical Shell

The method for setting the azimuth of the part is a fast, robust process that does not require precision placement of the holes holding the alignment spheres. This process is shown in cartoon form in Figure 11. First, the spindle axis (C axis) is rotated so that the spheres are roughly aligned vertically. Then the LVDT is used to trace across the lower sphere and the X position of the high point is noted. The LVDT is used to trace across the upper sphere and this high point's X position is also noted. The average of the two X positions is calculated and the X axis is move to this average position. The C axis is then rotated until the high point of the sphere is underneath the LVDT probe. The LVDT then probes the lower sphere to find the high point, and the average of the low point and the previous average is found. The axis is positioned, the C axis rotated, and the process is repeated until the high points of the upper and lower spheres have the same X value. The work coordinates of the machine are then set such that this rotational position of the C axis is 0°. From this point, the milling spindle can be used to mill lenslets on the exterior surface of the hemisphere. In the azimuth alignment process, an iterative method was chosen so that the placement of the holes for the alignment spheres was not critical. The iterative method relieves the need to have the holes at exactly the same distance from the center of the optic and any requirement on having them on true radial lines. Instead, the iterative method allows the alignment spheres to be positioned essentially anywhere since they will by default be positioned along a line and the line can be oriented vertically.

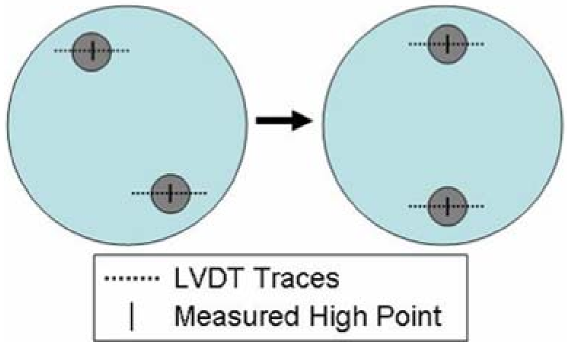

Figure 11. The LVDT Probe is Used to Trace the Top and Bottom Spheres in the X Axis Thus Locating the Highest Point of Each Sphere. The High Points Are Aligned Vertically and This Position of the Rotational (C) Axis Is Designated As 0°

Figure 12 shows the actual parts during the alignment process. This process was shown to have a repeatability of 0.002° which is significantly better than needed. Once the lenslets on the first side are machined, the optic is flipped over and the disk's OD is used to center the optic on the rotational axis of the spindle. The interior of the hemispherical shell is machined and the part is azimuth is then set by aligning the vertical axis of the spheres. It is important that the same sphere be positioned as the top sphere in this process.

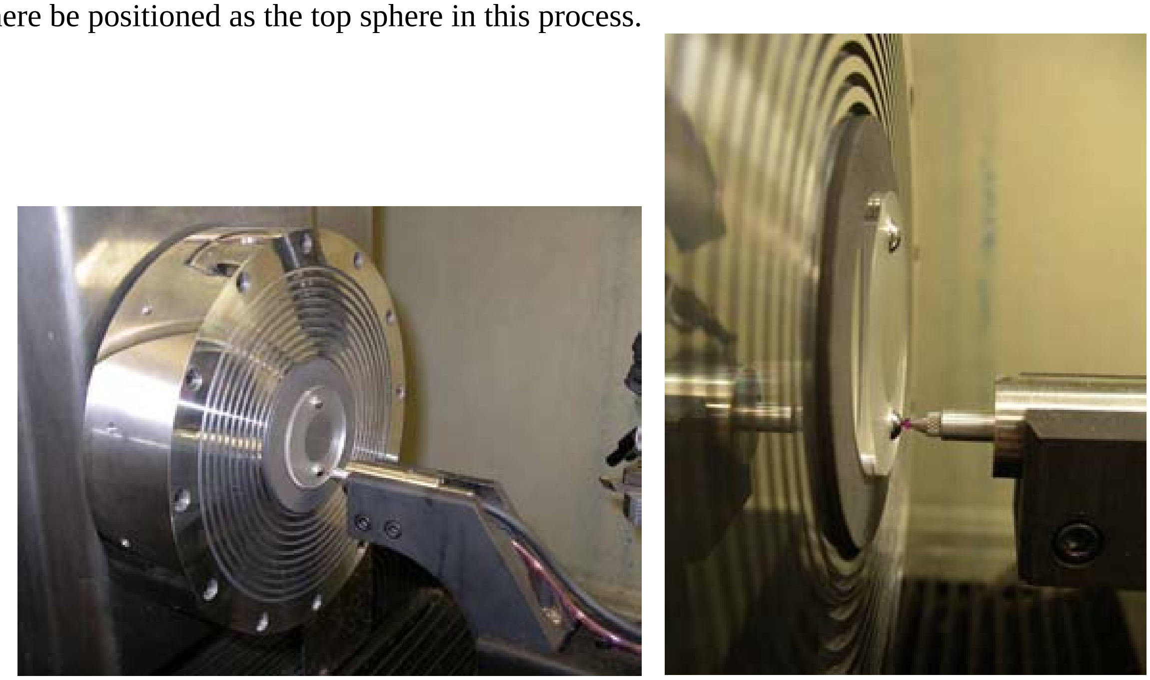

Figure 12. The LVDT Probe Is Used to Locate the High Points of the Two Precision Spheres. These High Points Are Aligned Vertically and the Rotational Axis Position is Designated As 0°.

3.4. Results of the Aspherical Milling

During research and development of the milling process, lens front and back facers were milled onto the surface of diamond turned flats as well as onto the surface of curved hemispherical surfaces. The optics turned out to be very difficult to measure. Methods utilized included white light interferometry, laser fizeau interferometry, and stylus probe metrology.

White light interferometry required the use of a 50X objective due to the high numerical aperture of the optic. This limited the measurement area to 185x243μm of the 600μm diameter optic. While this limits the usefulness of the data, the center of the optic can be measured which is important for determining the overall shape of the optic. Figure 13 shows a measurement of an optic milled with a spherical tool with two curve profiles taken through the center of the optic. Figure 14 shows the profiles again, this time with the curvature of the optic removed, leaving the residual error from a perfect sphere. This data shows the maximum error at the center of the optic to be 900nm (0.9λ) which is significant. This can be compared to the aspherical form that was removed from the diamond tool which had a departure of 1μm. This indicates that the error of this spherical tool is on the order of magnitude of the entire desired aspherical departure.

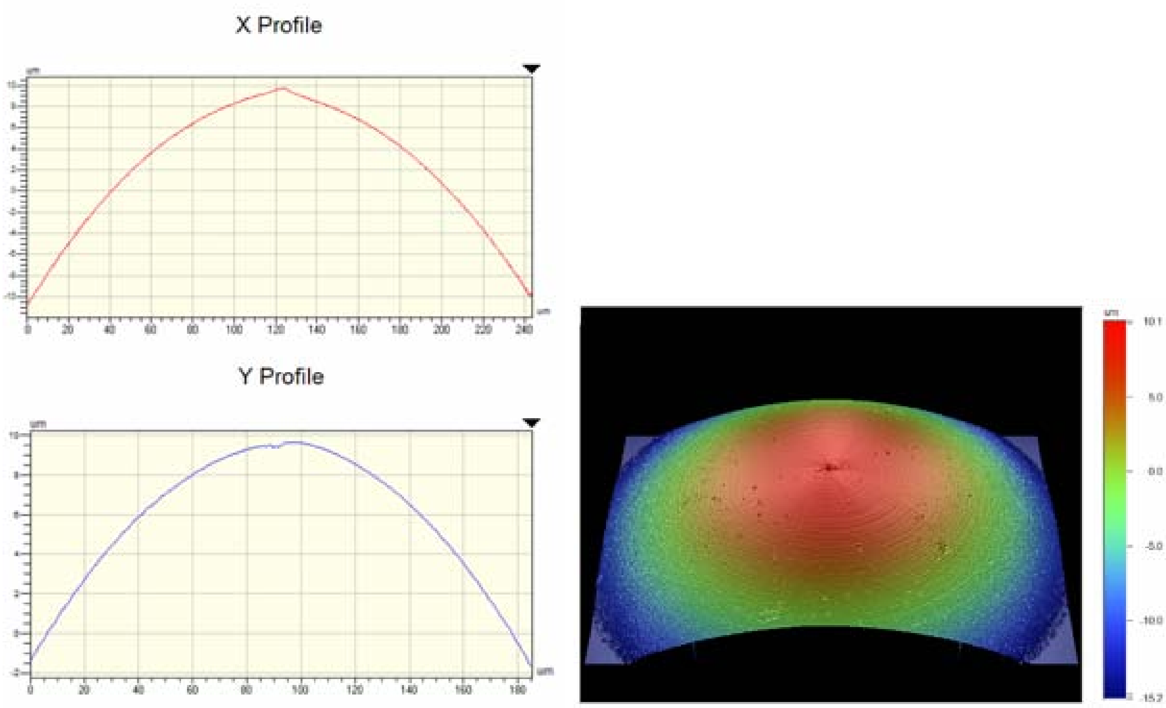

Figure 13. These Measurements Were Taken By White Light Interferometry and Show the Profile of the Center Portion of the Optic (185x243μm Patch of the Surface)

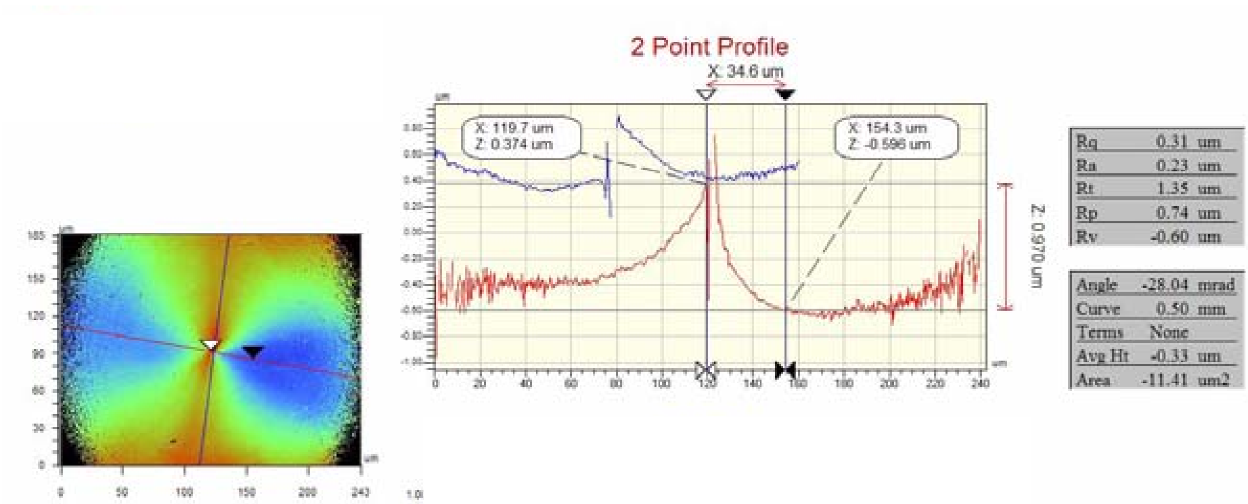

Figure 14. This Image Shows the White Light Interferometry Measurement with the Curvature Removed to Show Only the Departure from a Sphere. This Error Has a Peak Value of 900nm.

Because of the difficulty in measuring the shape of the optic, the team also attempted to measure the shape of the tools more directly. In these tests, the tool was scribed across the surface to leave the form of the tool as shown in Figure 15. In these tests, an unmodified (spherical) tool was scribed across the surface followed by a FIB modified (aspherical) tool. These scribe marks were then measured by a stylus profilometer. Unfortunately, the results of this measurement did not match any expected value and were far enough off to bring the measurements into question.

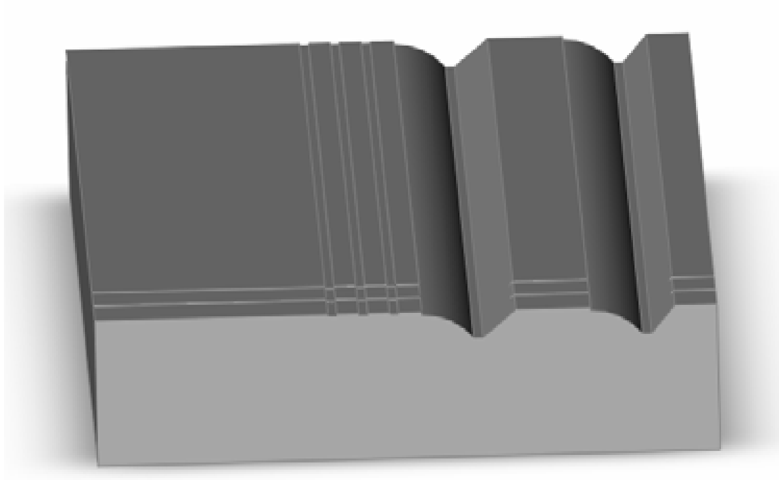

Figure 15. The Tools Were Used to Scribe the Surface to Leave Their Form. The Mark on the Left Signifies the Unmodified Spherical Tool and the Mark on the Right is a Modified Aspherical Tool.

Despite the difficulties in creating and measuring the aspherical micro optics, there was success in the demonstration of the ability to create small lenslets on the hemispherical surface of a turned optic. Figure 16 shows a prototype optic that was made with 7 lenslets milled into the surface of the turned dome. This exercise showed the viability of this technique. Unfortunately, time constraints prevented the final optic from being completed.

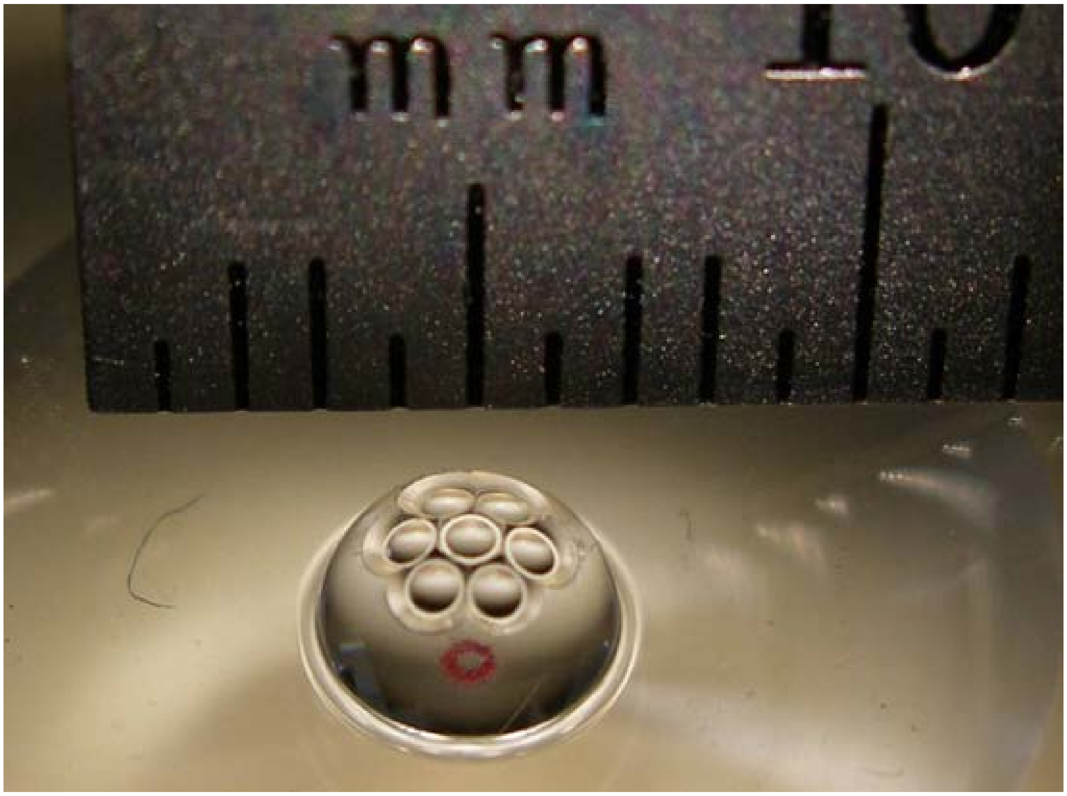

Figure 16. Aspherical Lenslets Milled into the Surface of a Turned Hemispherical Dome

3.5. Error Sources in the Milling Process

During the milling process, it became evident that there were several error contributors that were significant. The first was the radial error motion of the spindle / collet / mill system. The static radial error motion was measured manually at low speed, but it was difficult to isolate the error motion from the influence of the operator turning the spindle. Because the spindle does not operate well below about 12,000 rpm, and because the dynamic error is often a significant contributor in a system that operates at high rotational speeds, two fiber optic probes were purchased and a mounting yoke was designed and built to measure the error motion of the tool. This system is shown in Figure 17. The measurement yoke has 3 fiber holders mounted on micrometers. This allows the two fiber optic probes to be mounted opposing each other or 90° apart. The fiber optic probes have very high measurement rate making it possible to accurately measure the radial error motion of the tool at speeds up to 60,000 rpm. It is important to not that the micrometers are for adjustment only, and not for measurement purposes so the setup does not violate the Abbe Principal.

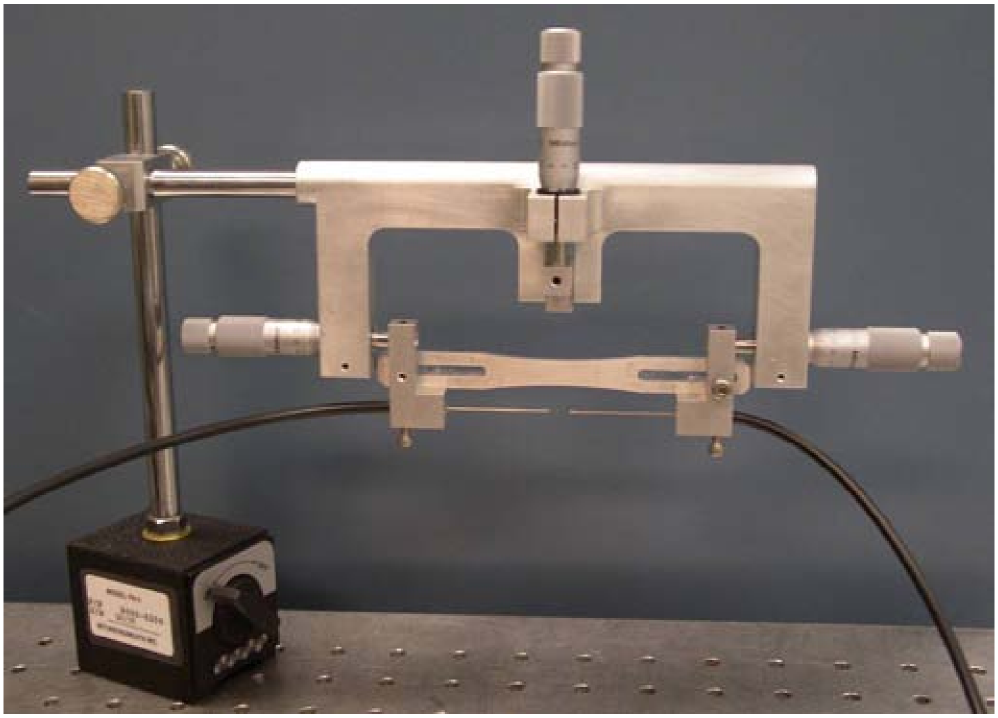

Figure 17. This Fiber Optic Probe Mount Was Designed and Built to Measure the Radial Error Motion of the Tool. The Tool Tip Is Positioned Between the Two Probe Tips at the Bottom of the Yoke and the Micrometers Are Used to Adjust the Position of the Probe Tips.

Using this measurement device, the error motion of the tool was measured. Because there is no reliable means of straightening a bent tool shaft, the only real adjustment that could be made was to rotate the tool in the collet and re-tighten. This was done until the minimum radial error value was determined. On all tools, this error motion was in excess of 7µm (on the diameter) as measured on the shaft of the tool as near the tool tip as possible. The fiber optic probes use a reflected signal off the surface of the shaft, so the area measured must be as uniform as possible which limited how close to the end of the shaft the measurement could occur, but it was still within 5mm in all cases. This large error quantity suggests that either the tool shafts were not straight or that the spindle in just too sloppy for use in this application. Because the tool shanks were centerless ground as longer stock, it is unlikely that the tool shank is responsible for a significant portion of the error. Instead, it is likely that the spindle rotational accuracy is insufficient for this application.

Another source of concern was that some milling conditions caused the tool tip to dance around on the surface. It was determined that this was due to asymmetric material conditions around the optic currently being milled. For instance, if an optic was milled in virgin material and then another was milled right next to it, the second optic would have a portion of the milling cycle where the back side of the tool was not cutting. Experiments showed that it was advantageous to mill the optics in an order such that the material conditions around the optic were symmetric.

Another condition addressed was the equalization of the forces on the tool during milling. Because the mill tool cuts both on the aspherical side and also on the back angle, it was thought that the forces generated by these edges might be forcing the tool in or out radially during the milling process. A calculation was performed to determine the optimal back angle such that the side forces resulting from the thrust force of the tool during plunge would be balanced between the aspheric side and the back angle side of the tool. The tool force model is shown in Figure 18. The calculation showed that there were two possible solutions for the back angle with β=71° giving the optimal solution because it would result in less force on the tool overall and because it would not have as significant an effect on possible spacing of the surrounding optics. These tools were ordered and delivered, but did not arrive in time to be used in this effort.

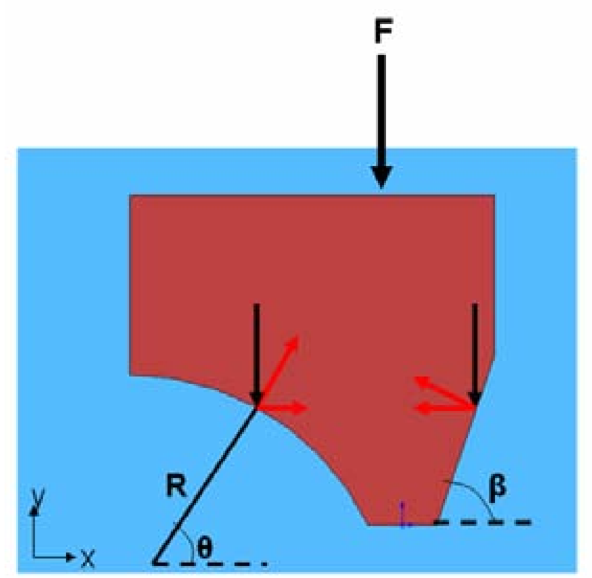

Figure 18. The Reaction Forces on the Curved Side of the Tool Match the Reaction Forces of the Back Angle When β=71° and the Tool Is Cutting at Full Depth

4. DIAMOND TOOL MODIFICATION BY FOCUSED ION BEAM MACHINING

Diamond milling offers significant advantages over on-center turning for the dragonfly eye application. However, no supplier was able to provide diamond mills with concave aspheres as needed to produce convex aspherical optics. The tool suppliers were able to supply spherical concave diamond mills with low waviness edges. Due to the tool manufacturing process, the suppliers were only able to promise a radius tolerance of ± 10μm. Because of Sandia National Laboratories' expertise areas of optical engineering and Focused Ion Beam (FIB) machining [3-5], it was determined that tool modification was not only possible, but would prove to be a valuable addition to the Laboratory's capabilities.

4.1. Diamond Tool Modification Overview

The tool modification process by FIB has many steps that are shown in Figure 19. The first step is the original, optimized optical design which requires the manufacture of aspherical convex microlenslets on the surface of the hemispherical optic that will be aligned with concave spherical optics on the inside of the hemispherical shell. From this design, the optic is inverted to a convex asphere and a best fit inscribed sphere is determined for the aspherical lenslets. This best fit sphere must be inscribed so that it contains excess material that can be removed by the FIB process to achieve the desired optic. The tool design is sent to the tool manufacturers who achieve the required design radius to ± 10μm. The actual radius of the tool provided by the suppliers is then inserted into the optical design and the design is tweaked to utilize this tool. The new optical design requires a new asphere and this asphere is fed into software developed for this project that determines the amount of material to be removed from the tool and the position of the material to be removed. This information is represented as a "mask" that is used by the FIB software to remove material from the part. It is in this manner that an optical design becomes a complex milling tool.

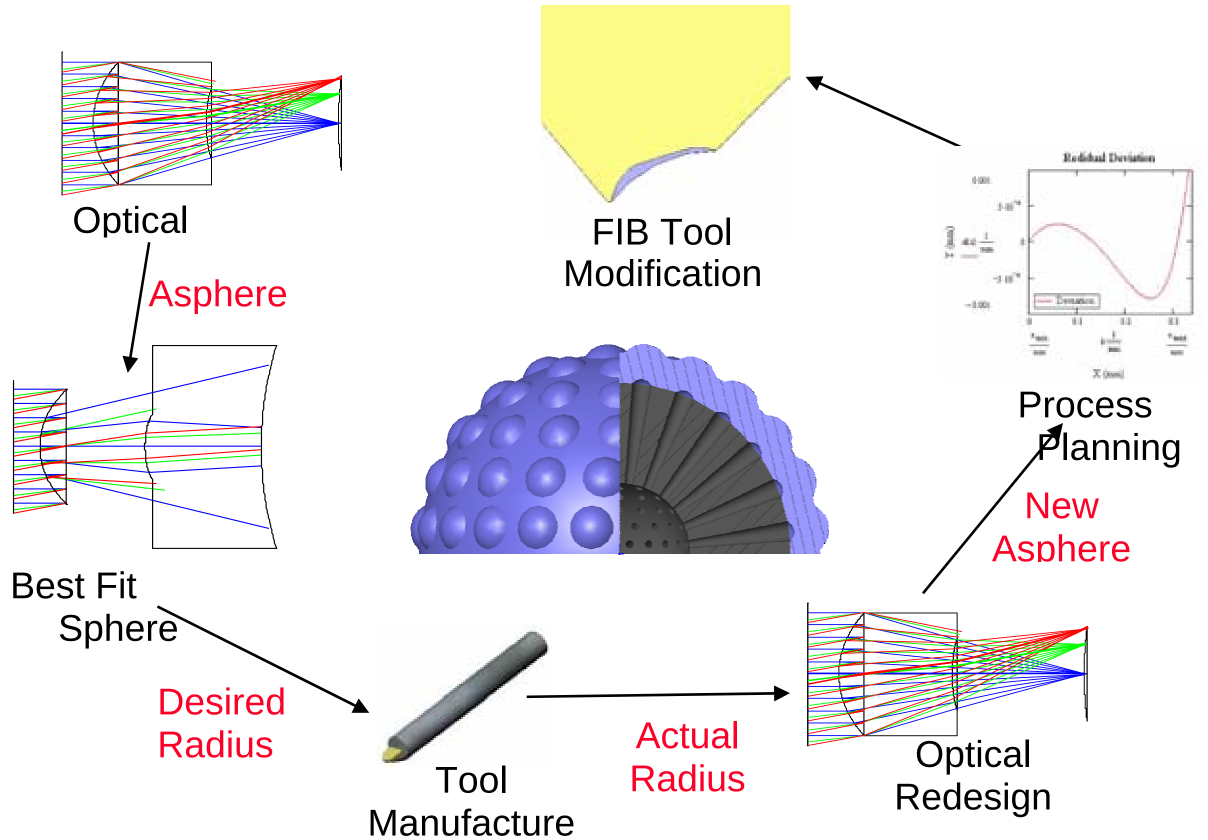

Figure 19. The Process Used to Modify Diamond Mills Using Focused Ion Beam Machining.

4.2. Aspherizing the Sphere – Modification of the Concave Diamond Mill

There are many steps to the actual FIB modification of the diamond milling tool. Initially, the tool had to coated in molybdenum and then overcoated in chromium. These layers were deposited on the tool as sacrificial layers to be eroded by the beam near the edges of the nearly Gaussian beam. This step is necessary to produce a sharp edge in the tool.

Next, the tool was mounted in a cassette that allows the tool to be tilted in 1 dimension in the machine. When mounting the tool in the cassette, it is necessary to align the tool so that the face of the tool is perpendicular to the beam direction in the vacuum chamber of the FIB. This alignment was done with a white light interferometer. The cassette is shown in Figure 20 with a tool mounted. The rotational capability of the cassette was used to create a clearance angle on the tool during the FIB machining process. The tool was aligned to 0.05° around its rotational axis for the FIB process.

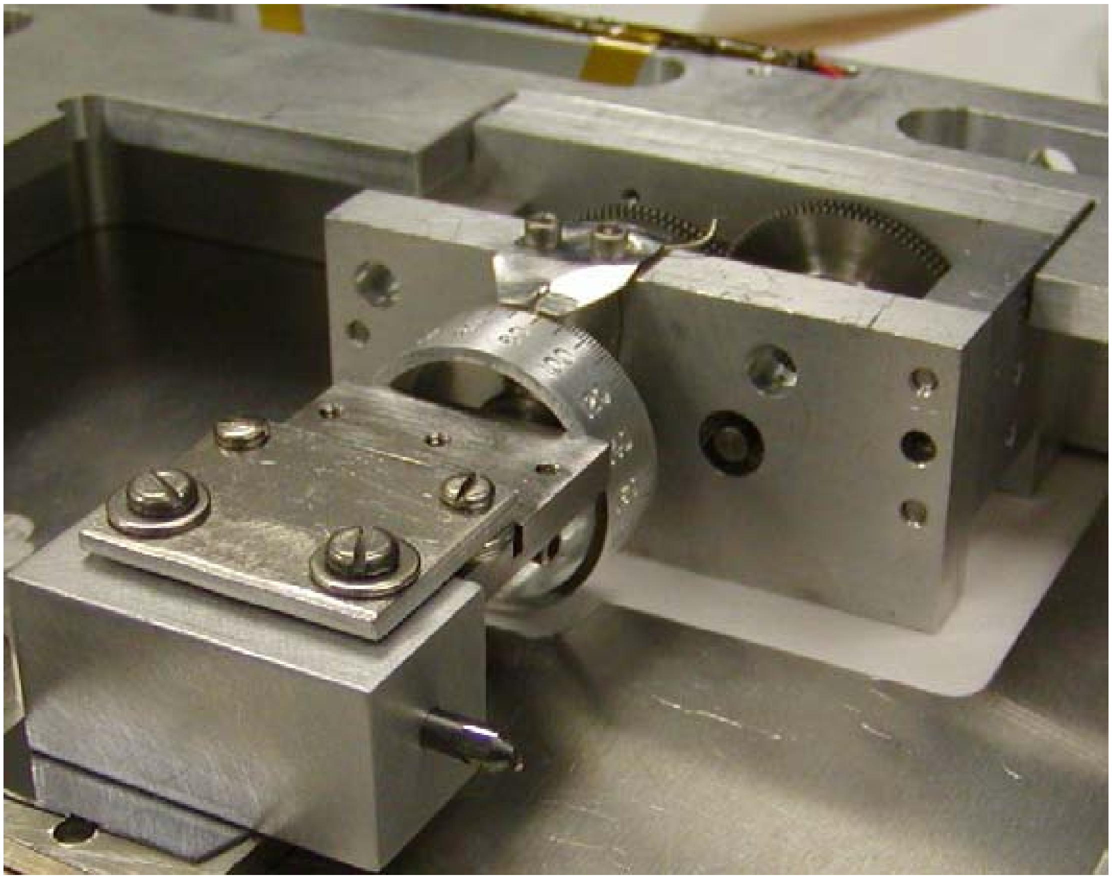

Figure 20. This Rotary Cassette Positions the Diamond Tool With Respect to the Incoming Ion Beam and Allows the Angle of Incidence to Be Adjusted. This Tilt Was Used to Give the Tool a Relief Angle in the FIB Milling Process.

The diamond tool and cassette were then mounted into the diamond turning machine. Testing showed that the best results could be attained using a beam energy of 30keV and a beam current of 7nA. The beam was used to illuminate the tool and secondary electron imaging was used to construct an image of the tool in the machine. This image was then aligned with the mask image that had been created using the mathematical definition of the asphere and the radius of the tool. Figure 21 shows the residual when the best fit inscribed circle is subtracted from the aspheric profile. This residual was used to create a mask that defined the material removal pattern for the FIB. This mask was then aligned to the image of the tool profile created from the backscattered electrons. The orientation and position of the mask is then sent to the focused ion beam machine. During this interval, the FIB was maintained at constant energy and current to help prevent any drift that occurs with shut down and restarts. The mask is shown positioned next to an image of the FIB machined tool edge in Figure 22. The FIB modified edge is the dark region at the curved cutting edge of the tool. Because of the clearance angle of the tool, anywhere that the cuts further back into the part, the FIB must also remove material over a increased depth. This results in an amplified view of the material removed. It can be seen that locations where the white region of the mask is wider, the depth of the dark section is also increased. The figure also shows a region of spots that were used to tune the beam calibration and dosage. The part was machined in 6hrs-45min.

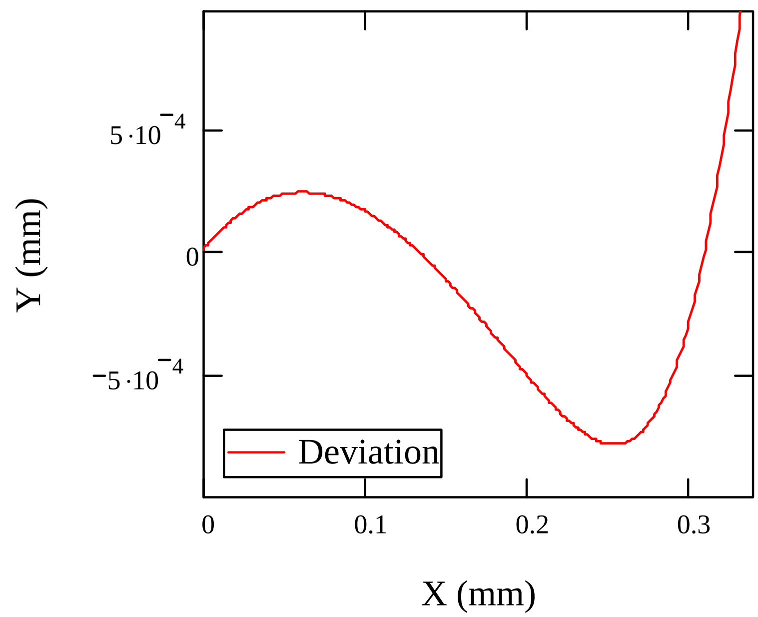

Figure 21. The Residual Deviation of the Aspherical Profile from the Best Fit Inscribed Sphere. This Deviation Was Used to Create a Mask Defining the Material Removal for the FIB.

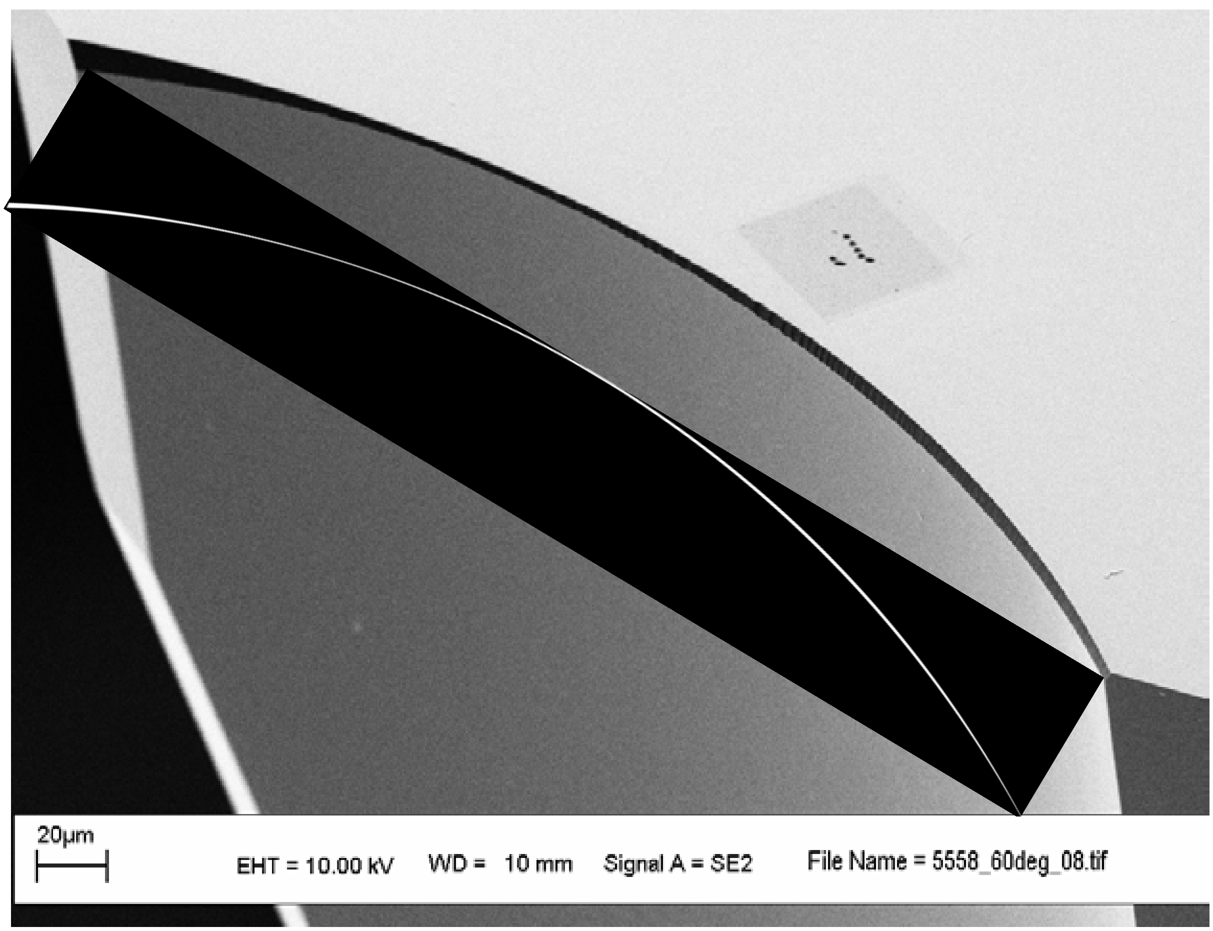

Figure 22. The FIB Modified Tool Edge is Shown with the Mask Overlayed. The FIB Modified Edge Shows as a Dark Band Near the Edge of the Tool.

5. CONCLUSIONS

The “Design and Manufacturing of Complex Optics” LDRD team set out to develop new methods of creating highly complex optical structures. The team chose the Dragonfly Eye optical array as a testbed for the processes and techniques developed during the research. The dragonfly eye is a 4mm diameter hemispherical polymer shell with an array of 660μm diameter aspherical convex lenslets machined into the exterior surface. These lenslets are aligned with concave spherical lenslets machined into the interior of the shell. The radial alignment tolerance was approximately 1μm requiring extremely repeatable machining methods to be utilized. Several options were considered, but the option with the best positional repeatability was determined to be plunge milling of the optics. In this method, the hemisphere is positioned on the chuck of the diamond turning machine and the diamond mill was put into the collet of a high speed milling spindle. The high speed spindle was mounted on a very repeatable indexing table. Through the utilization of the positionable spindle of the diamond turning machine and the indexing table, a very repeatable setup was created.

Plunge milling of aspherical convex optics required the development of new tool manufacturing methods. Tool manufacturers are only able to create spherical concave tools (which create convex optics in plunge milling) and had no means of creating aspheres. The project team developed a novel method for “asepherizing” the spherical tool utilizing focused ion beam milling. This method required significant interaction between optical designer, tool manufacturer, FIB process planner, and FIB operators to create the optimum tool while compensating for the inherent limitations of each manufacturing process. The tool was created and used to mill optics. Difficulties in the measurement of those optics have caused the team to not be able to fully characterize the success of the tool modification. In addition, the radial error motion of the spindle is much more significant than any error in the tool so full analysis of milled optics has been equipment limited thus far. The development of a means of creating aspherical convex micro optics by plunge milling is expected to be of significant interest to the optical industry. Also, the ability to manufacture highly complex optics has led to new customers with demanding applications.

6. REFERENCES

1. R. Hornsey, P. Thomas, W. Wong, S. Pepic, K. Yip, R. Krishnasamy, *Electronic Compund-Eye Image Sensor: Construction and Calibration*, Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications V., Proceedings of the SPIE, Vol. 5301, pp. 13-24 (2004)
2. J. Duparre, P. Dannberg, P. Schreiber, A. Brauer and A. Tunnermann, "Artificial apposition compound eye fabricated by micro-optics technology," Appl. Opt. 43, 4303-4310 (2004).
3. Adams, D.P., Vasile, M.J., Krishnan, A.S.M., 2000, Microgrooving and microthreading tools for fabricating curvilinear features, *Precision Engineering*, 24: 347-356.
4. Adams, D.P., Vasile, M.J., Benavides, G., Campbell, A.N., 2001, Micromilling of metal alloys with focused ion beam-fabricated tools, *Precision Engineering*, 25: 107-113
5. Picard, Y.N., Adams, D.P., Vasile, M.J., Ritchey, M.B., 2003, Focused ion beam-shaped microtools for ultra-precision machining of cylindrical components, *Precision Engineering*, 27: 59-69

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