

# DEVELOPMENT AND ANALYSIS OF AN OPTICAL CAPABILITY FOR THE MEASUREMENT OF ARRAYS

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## INTRODUCTION

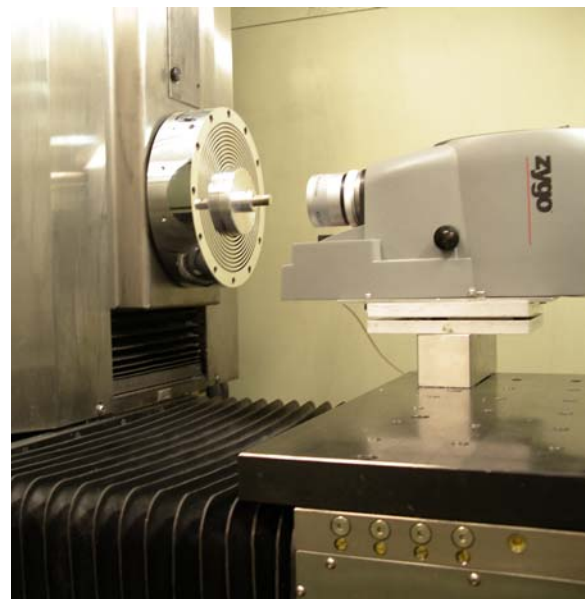
The Mesoscale Manufacturing and Systems Development Department at Sandia National Laboratories has developed the capability to measure optical arrays in response to customers' needs. It has been a specific need to measure an array of miniature spherical optics where the optical surface was only a very small spherical surface patch. Previous attempts to use a coordinate measuring machine proved to have too much uncertainty due to the very small portion of the spherical surface available for measurement. In response, a small form-measuring interferometer was mounted in a 4-axis diamond turning machine. This combination allowed the high accuracy positioning of the diamond turning machine to be utilized with the capabilities of the interferometer, which has proven to be a very versatile tool. In addition to the measurement of optical arrays, the system allows rapid measurement of diamond turned surfaces for tool centering, tool radius error compensation, feature positioning, and part radius of curvature measurements.

This paper includes a description of the system, the results of an uncertainty analysis, and applications for which this system is proving most useful.

## SYSTEM DESCRIPTION

The multi-axis interferometer system utilizes a Zygo PTI 250P form measuring interferometer, a Moore Nanotechnology Systems 350FG 4-axis diamond turning machine, and a kinematic mount for repeatable positioning on the Z axis of the machine tool. The first iteration of utilizing the interferometer in the diamond turning machine is shown in Figure 1. The interferometer is mounted in the machine and then adjusted in pitch and yaw such that it is aligned with a surface, such as the vacuum chuck, which has been diamond turned in the machine and is thus assured of being aligned to the axes of the machine. In this machine, the

interferometer is on the Z axis while the part to be measured is on the spindle C axis which is mounted in the Y axis and stacked on the X axis. This setup allows the interferometer to move in only one axis while the part moves in three axes. This is helpful, especially with cable management from the interferometer. The interferometer is attached to a kinematic mount because it is often necessary to remove the interferometer from the machine. When this occurs, the kinematic mount is covered to preserve cleanliness.



*FIGURE 1. The interferometer (right) is shown mounted in the diamond turning machine on the Z axis. The spindle axis, holding the workpiece to be measured, is mounted in the Y axis which is stacked on the X axis of the machine tool.*

The interferometer matches this application well due to its small size and low weight making it easy to install in the machine over and around other turning tools and equipment. The maximum aperture of the interferometer is 25mm which is sufficient for many of the surfaces created by the authors. The PTI 250P utilizes a temperature stabilized solid state laser

which keeps the power consumption and subsequent heat generation to a minimum within the machine environment. The turning machine shell was modified to have a through hole allowing for cables to enter the machine. The power and communication cables extend from the interferometer to the computer and its image capture board which is kept outside the machine. The interferometer has bayonet mount transmission spheres and flats, giving easy and repeatable optics interchangeability.

The Nanotechnology Systems 350FG is a 4-axis precision machining center with X,Y,Z motion and a positionable spindle (C axis). The machine has demonstrated form accuracy better than 100nm over a 75mm spherical test part for the linear axes and has a stated accuracy of  $\pm 2$  arcsec for the spindle C axis.

The initial iteration of testing, shown in Figure 1, utilized available tooling blocks which required that pitch and yaw adjustment of the interferometer be achieved by manually “tapping in” the mount and by shimming the mounting plate. The tooling block was not well suited for this task due to the large cantilevered portions of the interferometer. To address these concerns, a new mount has been designed that gives the user micrometer adjustments of pitch and yaw while giving the interferometer better support over its entire base. The improved mount was not completed in time for this submission but will be discussed at the poster presentation.

**UNCERTAINTY ANALYSIS**

In order to utilize the system for customer needs, an uncertainty analysis was performed for the whole system. Because of the information available at the time, the uncertainty analysis has the flavor of an error budget. The analysis included error contributions from temperature effects, the kinematic mount, the interferometer laser, and the machine axes. In addition, it was determined that the most conservative method for the analysis would be to include a Repeatability and Reproducibility (R&R) study of the whole system including operator variability.

**Repeatability and Reproducibility Procedure**

The R&R utilized 3 operators taking measurements of a diamond turned concave spherical surface over the course of 3 weeks. The test surface has an aperture of 0.5 inches and was measured with an f/1.5 transmission

sphere. The interferometer and kinematic mount were positioned in the machine using a transmission flat and the diamond turned face of the machine’s vacuum chuck was used to align the interferometer to the machine axes. After this initial alignment, the pitch and yaw axes of the kinematic mount base, and thus of the interferometer, were not adjusted for the duration of the 3 week test. However, each operator lifted and replaced the interferometer on the kinematic mount before that day’s measurement. The operator then moved the axes to locate the reference surface with the interferometer, and took measurements of the part. Within a set of measurements (for all 3 operators on a single day), the measured surface stayed fixed to the vacuum chuck, but between days it was necessary to remove the part due to other machine usage. The interferometer was removed from the machine each day after data collection, but remained powered on for the duration of the 3 week testing.

The measurement procedure required that the operator find the catseye position for rough positioning and then move to the confocal position. The operator took multiple measurements of the surface and moved the machine along the Z (optical) axis until the measured power was minimized. At this point, the axis location, optical power, form PV, form RMS, and the 10<sup>th</sup> order Zernike polynomial terms were noted and the machine was moved in X, Y, and Z before beginning the next operator’s measurements. The results of the R&R study are shown in TABLE 1. The table presents results for machine position (position of the confocal point representing the center of the measured sphere) and for the PV and RMS form errors measured by the interferometer at the confocal position.

*TABLE 1. Standard deviation determined from the R&R study for machine position of the confocal (sphere center) location in X, Y, and Z, and PV and RMS form errors measured at the confocal point. The part position was different each day so measurements within a day were compared and the resulting deviations averaged.*

$\sigma_x$ (mm)	$\sigma_y$ (mm)	$\sigma_z$ (mm)	$\sigma_{PV}$ (nm)	$\sigma_{rms}$ (nm)
0.00507	0.00207	0.00141	2.847	0.591

### **Error Budget Results**

The thermal, interferometer, axes, and kinematic mount error contributors were assumed to have rectangular distributions while the R&R results were assumed to follow a normal distribution. For each contributor, the variance was determined and totaled for all error sources. The total system standard deviation was determined from the variance and a factor of 2 standard deviations is reported as the expanded uncertainty for the system giving a 95% confidence interval. The results of the uncertainty analysis are given in TABLE 2.

TABLE 2. Results of the expanded uncertainty analysis. See Discussion section for explanation of error sources.

	X	Y	Z
Expanded Uncertainty	10.35um	4.69um	3.30um

### **R&R Discussion**

As is common in this type of analysis, the results of the R&R study overwhelmed the other error contributors. There are several proposed causes of the poor performance of the system in the R&R study. The initial implementation of the system utilized already existing tooling blocks which were not well suited for the application. The interferometer was cantilevered a long distance over the tooling block leading to a possible lack of repeatability in positioning the system. A second issue was poor cable management. Because the interferometer had to be placed in the machine and removed after every test, the cables were not permanently affixed to the axis to give uniform cable strain. This strain primarily causes a yawing of the interferometer on the mount and is expected to be the source of the large X uncertainty. In future testing, the cable will be fitted with a cable tie to attach to a bolt on the Z axis so that the cable strain will be more uniform in testing. A third source of error is the utilization of inexperienced students for the testing. This was determined to be the most conservative method of testing. The operators were all students who had no prior diamond turning or interferometric metrology experience. A set of work instructions was created for the students to follow, and they followed it carefully. Where an experienced operator might have a bit better perspective on the measurement and how to achieve the most accurate measurement, the students primarily followed the work instructions and any deficiency in the instructions was directly transferred to the results. A fourth source of

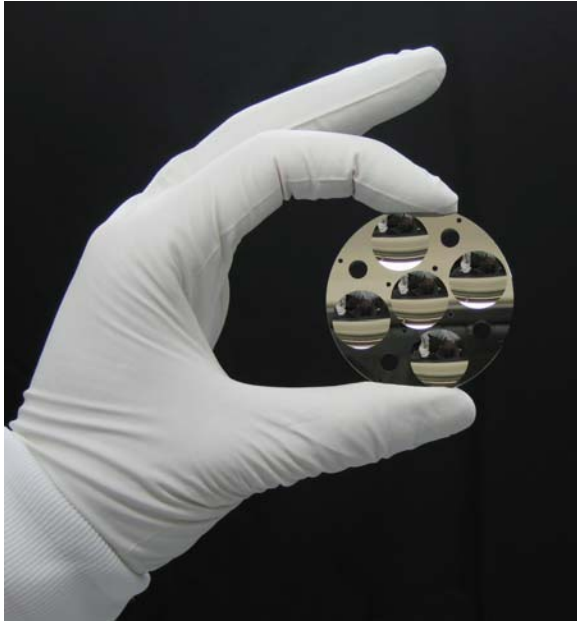
error was improper maintenance of the kinematic mount. The mount was new and was not properly lubricated. The newness and the lack of lubrication may have had a small contribution to the error by changing the interferometer's position over time. And finally, a source of concern for the mathematics of the R&R was the necessity to remove the measured artifact from the machine every day. The removal of the artifact meant that the X, Y, and Z positions could only be compared within a day's testing (3 operators taking 1 measurement each). Having only 3 measurements for the day makes the day's standard deviation a bit questionable. This was a tradeoff between doing all of the measurements back to back or doing all of the measurements across a span of 3 weeks to include environmental fluctuations in the study. The authors have designed a new mount for the interferometer and plan to try the R&R study again with the operator testing being done consecutively allowing the artifact to remain in the machine. Additionally, the mentioned cable holder will be utilized as will updated work instructions.

### **APPLICATIONS**

The interferometer/diamond turning machine combination has proven useful for many applications. The most basic of these is for tool centering. Typical tool centering for a research machine (i.e., one that is using a variety of tool geometries, setups, cutting planes, etc.) requires that the rough position of the tool is found using an optical tool setter or by eye. The height of the tool is then fine tuned by cutting a spherical surface and measuring the diameter and shape of a center residual feature. And, finally, the feed axis (X) position is fine tuned by cutting the spherical surface and measuring the form. In addition, tool radius errors can be determined if there is a means of measuring the radius of the surface. When using this methodology, it is usually necessary to take the part out of the machine after each cut of the spherical surface. In many instances, this will require that the part be removed from the machine many times. Each time, the part must be centered again when it is put back on the spindle. However, the introduction of the interferometer in the machine tool allows the tool to be centered without the part having to leave the machine. This results in a great time savings.

Another example part is the metrology target shown in Figure 2. Several of these parts were

diamond turned on Sandia's 350FG. Two of the optics were mounted in an assembly and the customer needed to know the position and radius of each of the 10 optics in the assembly. The spherical optics contain only a small surface patch of the sphere, so CMM measurements were not felt to be of sufficiently low uncertainty. Instead, the assembly was placed in the diamond turning machine and the interferometer was used to measure position and radius for each of the 10 optics in reference to an origin also measured on the part. This system provided valuable information in a short timeframe for this customer.



*FIGURE 2. An example application for the reported measuring capability was this metrology target for which the customer needed to know optical radius and position for the 5 optics with respect to each other and 5 other optics in and assembly.*

#### **ACKNOWLEDGEMENTS**

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