Developing on-machine 3D profile measurement for deterministic fabrication of aspheric mirrors

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Synopsis by Richard Pultar

Abstract

This synopsis covers the work done by Dong et al. in developing an on machine three-dimensional profile measurement system (JR-1800). Investigations into mechanical errors, misalignment, output stability, temperature variations, and natural vibration were performed. The system was tested by comparing measurements of a reference workpiece from the JR-1800 and an interferometer. An RMS repeatability of ~$\lambda/30$ (λ = 632.8 nm) and RMS deviation of 0.07 µm between the JR-1800 and interferometer was found.

Introduction

Aspheric segments are used in many optical systems, such as intense laser systems, astronomical telescopes, beam expanders, and photolithographic systems. Aspheric components can improve image quality while reducing size and weight making them a valuable resource for next generation optical systems. However, due to varying curvature fabrication and metrology and of aspheric elements is challenging.

Fabrication of an aspheric optic typically involves three steps: (1) grind the blank to the desired shape using diamond tooling, (2) lapping of the surface to reduce surface roughness and remove sub-surface damage, and (3) iterative deterministic polishing to achieve final surface form and roughness.

Utilizing deterministic polishing the surface peak to valley (PV) error can be reduced to tens of nanometers, however this relies on measurements made by interferometers or other surface profilometers. Interferometric methods require a specular surface which pose problems in the early stages of fabrication. Infrared interferometry can be used, but it is expensive and has a lower sensitivity than shorter wavelength interferometers. Interferometry of aspheric surfaces also requires null compensators, computer generated holograms, or stitching methods which add to complex testing setups and can increase cost.

Commercial profilometers are available such as the Form Talysurf PGI 1240, multiprobe bar profilometer by Itek, and the Leitz CMM. Each of these has drawbacks though, such as limited dynamic range, costly references, and they require the part to moved off the polishing machine. For these reasons the authors developed the JR-1800, a system for fabricating plane, spherical, and aspherical optics with on machine 3D profile measurement capability utilizing a length gage. This paper focused on the 3D measurement capability and provides a detailed investigation into the mechanical errors of the JR-1800, misalignments of the length gauge and workpiece, output stability of the length gage, temperature variation, and natural vibration.

Background on Profile Measurement

A. Aspheric Surfaces

An aspheric surface can be expressed by Eq. 1, where C = 1/R (R is the vertex radius of curvature), K is the conic constant, n is the aspheric order, and A_{2i} is the high-order aspheric coefficient.

$$Z(X,Y) = \frac{C\left(X^2+Y^2\right)}{1+\sqrt{1-(K+1)C^2\left(X^2+Y^2\right)}} + \sum_{i=1}^{n} A_{2i}(X^2+Y^2)^i \tag{1}$$

Off axis aspherics are of particular interest for reflective cameras, collimating devices, etc. Figure 1 shows an example of a parent mirror with two off axis configurations, OA-I and OA-II. OA-I can be described by Eq. 2 below,

$$Z_1(X,Y) = \frac{C\left(X_1^2+(Y_1-y_0)^2\right)}{1+\sqrt{1-(K+1)C^2\left(X_1^2+(Y_1-y_0)^2\right)}} - z_0 \text{, } \tag{2}$$

and OA-II can be described by Eq. 4, using the transformation matrix given in Eq. 3 and the definitions in Eq. 5.

$$\begin{vmatrix} X' \\ Y' \\ Z' \\ 1 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) & 0 \\ 0 & \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} X_1 \\ Y_1 \\ Z_1 \\ 1 \end{vmatrix} \tag{3}$$

$$Z' = \frac{-B+\sqrt{B^2-4AQ}}{2A} \tag{4}$$

$$\begin{cases} A = C + KC\cos^2(\theta) \\ B = (-2CY'\sin(\theta)\cos(\theta) - 2Cy_0\sin(\theta) - 2\cos(\theta) + (K+1)C(2z_0\cos(\theta) + 2Y'\sin(\theta)\cos(\theta))) \\ Q = 2z_0 + 2Y'\sin(\theta) - (K+1)C(z_0^2 + 2Y'z_0\sin(\theta) + Y'^2\sin^2(\theta)) - C(X'^2 + Y'^2\cos^2(\theta) + 2Y'y_0\cos(\theta) + y_0^2) \end{cases} \tag{5}$$

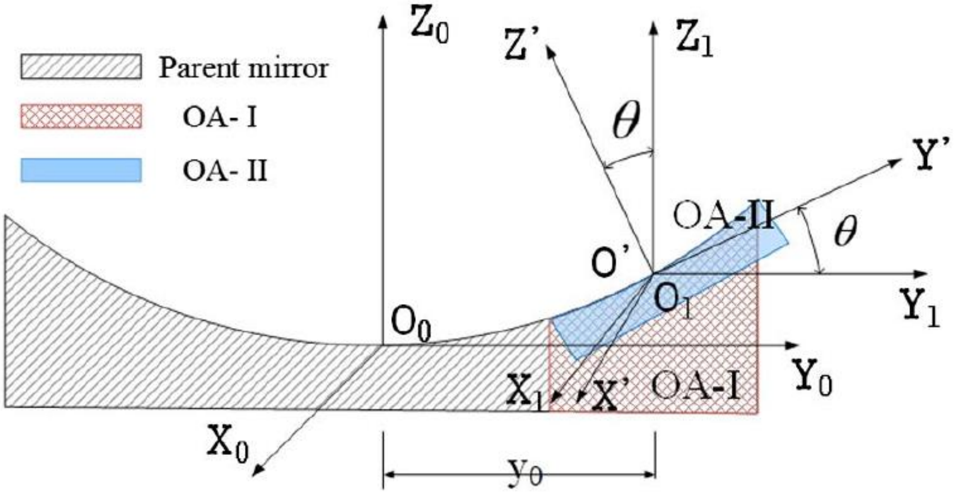

Figure 1. Sketch of aspheric surface

B. JR-1800 Measurement System

As shown in Figure 2, the JR-1800 is a gantry type polishing machine with built in measurement capability. It is built on a marble base 3200 mm x 4000 mm x 620 mm supported by a vibration free groundwork. The XYZ axes have a travel range of 1840 mm x 2096 mm x 603 mm and the C axis has a diameter of 1800 mm. The JR-1800 is capable of fabricating and testing plane, sphere, and aspherical parts up to 1800 mm in diameter.

A MT60 length gage with tough trigger probe, commercially available from Heidenhain is used. The MT60 uses optical linear encoders the measure the extended length of its plunger and has a maximum travel of 60.8 mm. This large travel range allows the Z axis to remain stationary when testing eliminating any potential errors from positioning the Z axis. The Abbe offset of 225.7 mm between the Z axis and plunger is also eliminated by not moving the Z axis.

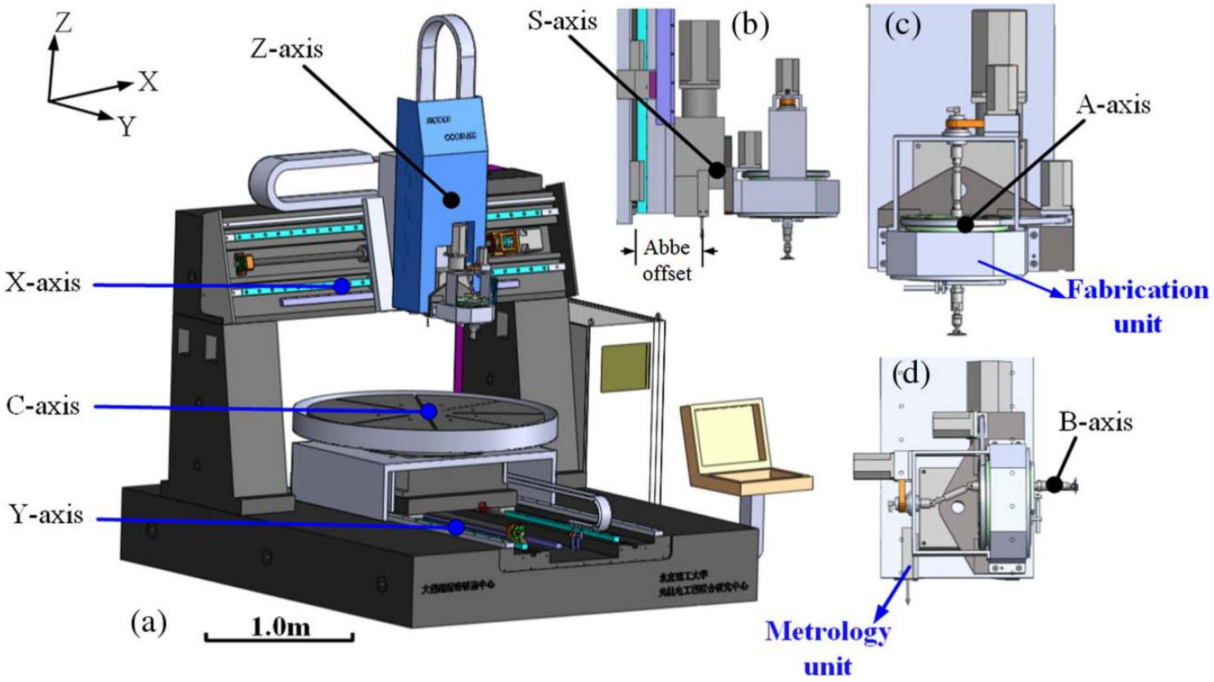

Figure 2. Illustration of JR-1800; (a) overall view; (b) side view of metrology and fabrication unit; (c) fabrication status; and (d) metrology status.

The JR-1800 can be used in XY and XC modes where discrete data points are collected while positioning the workpiece and touch probe with the respective axes. Compared to interferometry, some notable characteristics of the JR-1800 are:

1. Any surface shape can be measured without the need for null correctors, computer generated holograms, or other compensators.
2. Both specular and non-specular surfaces can be measured making it useful in the early stages of fabrication.
3. Sag heights are directly measured allowing for analysis of vertex curvature and conic constant, which are not immediately available from interferometric testing.
4. An accuracy of ~1µm is expected, which is much lower than that of an interferometer.

(5) The time it takes to measure is dependent on how many points are collected and how fast those points can be collected. Typically, 1000-1200 points are collected per hour. By not having to remove the workpiece measuring times similar to interferometric testing are achieved.

Calibrations and Alignments

A. Calibration of Mechanical Errors

Mechanical errors, such as linearity error of guide rails, positioning error of axes, etc will influence the measurement results. The mechanical errors are invariant through time and can be calibrated and compensated for. The authors found that the XY axes had a positioning erros less than 6.0 µm and 9.2 s for the C axis. Repeatability errors for the XY axes was ~3.3 µm and 4.3 s for the C axis. The linearity of the X axis was found to be 1.75 µm.

The radial and axial runout of the C axis, parallelism of the X axis and turntable, perpendicularity of the XY, XZ, and YZ axes also have effects on measurement errors. However, the authors found these errors difficult to correlate with the measurement results.

To calibrate the system a 440 mm x 440 mm reference window with PV = 0.23 µm was used. In XC mode a PV = 2.3 µm and RMS = 0.38 µm was measured. In XY mode a PV = 3.0 µm and RMS = 0.53 µm was measured. These errors maps were then used to calibrate the system and must be removed from all measurement results. Since only a 440 mm x 440 mm reference was used these error maps can only be used over that same area.

B. Alignment of the Length Gage and Workpiece

There are three coordinates of interest when aligning the measuring probe to the workpiece: (1) the center of the turntable, (2) the workpiece coordinate defined by its vertex, and (3) the probe coordinate defined by its spherical tip. Figure 3 shows these coordinates both misaligned and aligned.

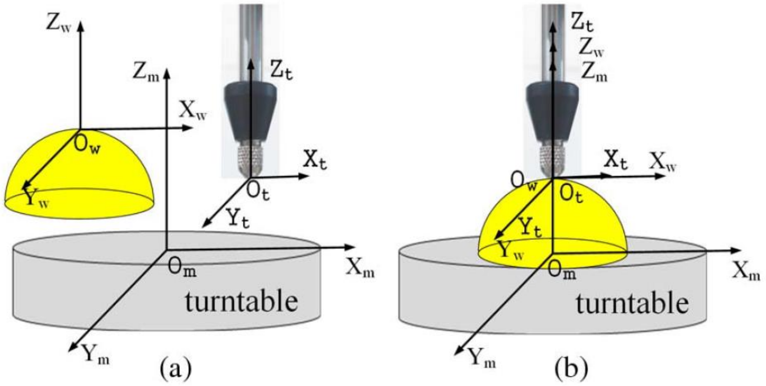

Figure 3. Measurement coordinates of JR-1800 (a) misaligned (b) aligned

It was shown that positioning error of the tool in the X direction produces a linear error, proportional to X position. It was also shown that this error is proportional to F/# of the workpiece, higher surface slopes produce higher measurement errors.

To align these coordinates the workpiece is first centered to the turn table using a dial gage contacting the edge of the workpiece. The workpiece is rotated and the workpiece is moved until the dial gage indicates less than 0.001 µm of runout. To align the measuring probe to the workpiece a profile is measured in the

X direction, followed by a profile in the Y direction. Using these profile deviations from theoretical values the probe can then be repositioned. This offset position could be limited to ±5 µm with this method.

C. Output Stability of MT60

When the MT60 contacts the surface being measured there is measurement instability. The measurement can vary ~0.02-0.05 µm. To limit this error reading times from n = 1 to n = 200 were considered. It was found that after n = 20 the measured PV value can be controlled to within 0.08 µm.

D. Influence of Temperature on Measurement Results

To consider thermal effects, the authors preformed a finite element analysis of the system. The JR-1800 was meshed with a size of 50 mm for a total of 731,444 elements. The reference temperature was 20ºC and an increase in 1ºC was considered. The maximum deformation was found to be ~23 µm and the deformation difference at points A and B in Figure 4 was found to be 0.91 µm/ºC. Because of this the temperature of the system if maintained to 20 ± 0.2ºC, producing a maximum error due to temperature of ±0.182 µm. The authors also considered the deformation of the MT60 touch probe, which deforms 0.16 µm/ºC for a total deformation of 0.032 µm over the operating range. Also, the workpiece needs to be accounted for and should be modeled for each workpiece.

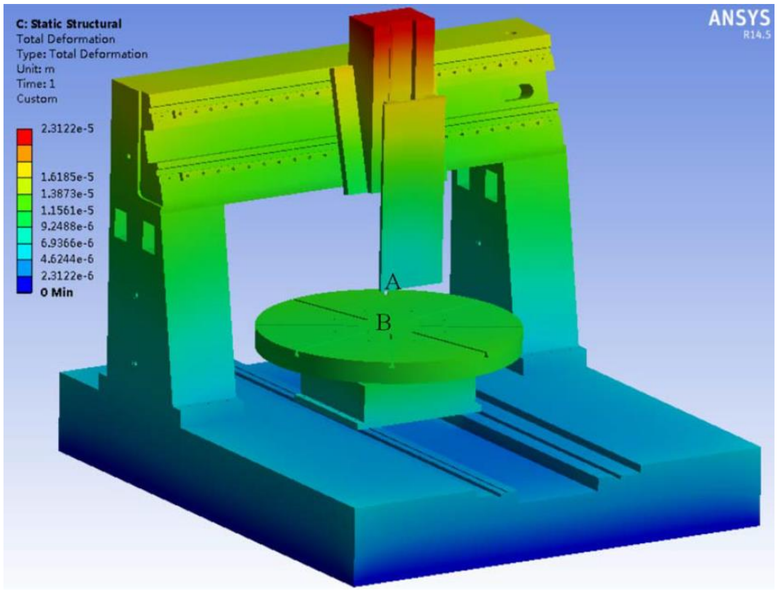

Figure 4. Deformation of system with temperature difference of 1ºC

Error Compensation

A. Tool Radius Compensation

As shown in Figure 5 the spherical probe tip will induce a nonlinear error into the measurements. To eliminate this error the theoretical sagittal deviations of points U and P are added or subtracted to the measurement and can be found using Eq. 6.

$$Z_{UP} = Z\left(\sqrt{X_P^2 + Y_P^2} + R_t \sin(\gamma), 0\right) - Z\left(\sqrt{X_P^2 + Y_P^2}, 0\right) - R_t(1 - \cos(\gamma)) \quad (6)$$

B. Tilt and Offset Compensation

To eliminate residual misalignment as shown in Figure 5, the authors used a least-square algorithm. Using the discrete points measured, the algorithm can compute the compute the final surface form.

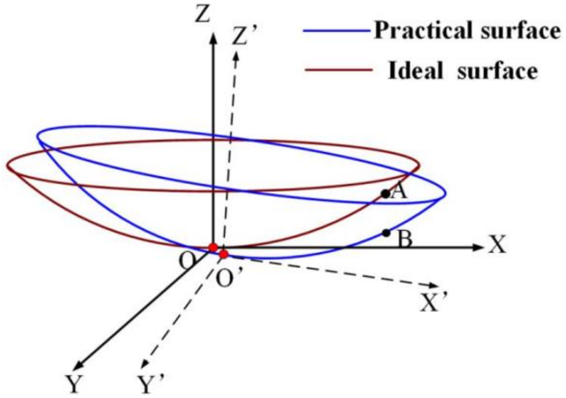

Figure 5. Practical vs. Ideal surface position due to residual misalignment.

Validation Experiments

A. Repeatability and Accuracy

To determine repeatability and accuracy the authors measured an optical flat with a diameter of 400 mm. Using a concentric circle path with points spaced every 8 mm for a total of 2030 points the RMS deviation of three measurements was las than 1/30λ. The measurement error when compared to results from a 24 in. Zygo interferometer had PV = 0.247 µm and RMS = 0.042 µm. From these results the authors determined that the JR-1800 measurements could be used for feedback during the initial phases of grinding and polishing optical mirrors.

B. Validation for Aspherical Mirrors

To verify performance on aspherical mirrors a paraboloid with diameter of 320 mm and R = 4000 mm was used. Again, using a concentric circle path with 2900 points and 15 mm spacing, the measurement error PV was 0.512 µm and RMS was 0.067µm**.** The authors also determined this to be useful for feedback during the initial phases of grinding and polishing aspheric mirrors.

Conclusions

The authors of this paper provide a comprehensive overview of the JR-1800 3D profile measurement system. The measurement errors induced by machine axes misalignment, misalignment of the length gage and workpiece, length gage stability, temperature variation, and natural vibrations were all considered. Those that could be calibrated or quantitatively compensated for were. The remaining effects were considered when determining measurement limitations and determining the appropriate use of the gathered data. This measurement system cannot be used to verify a completed optic as an interferometer would, but is useful as an in situ test to guide the earlier fabrication processes.

References

1. Zhichao Dong, Haobo Cheng, Xu Ye, and Hon-Yuen Tam, "Developing on-machine 3D profile measurement for deterministic fabrication of aspheric mirrors," Appl. Opt. 53, 4997-5007 (2014)