Fast and accurate measurement of large optical surfaces before polishing using a laser tracker

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We present a method that accurately measures large optical surfaces before polishing using a laser tracker. Using the scanning mode of the laser tracker considerably improves measurement efficiency and minimizes the dominant errors caused by environmental change. We use this method to measure a Φ1.3-m aspheric mirror and obtain a measurement uncertainty of 0.72 μm (root mean square, RMS).

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Large optics requires the fast and accurate measurement of surface shape[1,2]. As examples, the thirty meter telescope (TMI) and the extremely large telescope (ELT) consist of hundreds of segment mirrors with sizes ranging from 1 to 2 m, and each mirror should be accurately measured by different fabrication processes[1,2].

Researchers have proposed various methods of measuring large mirrors, one of which is laser tracker measurement, which has been proven effective in measuring large mirrors before polishing[3,4]. Laser tracker is essentially a flexible coordinate measurement machine that measures spherical coordinates instead of Cartesian coordinates. The tracker uses a distance measuring interferometer (DMI) to measure radial distance, and two angle encoders to measure rotation angles. A sphere-mounted retro-reflector (SMR) is used as a probe to obtain object information. A position-sensitive detector detects the SMR's motion and keeps tracking. Current commercially available laser trackers provide two modes of measurement, namely, static and scanning measurements, and mode selection depends on the SMR's motion during measurement. The flexibility of laser trackers enables surface measurement without restrictions on mirror diameter, and eliminates risks from mirror transport.

Nonetheless, commonly used static sampling strategies have two deficiencies: 1) contact measurement requires numerous sample points, indicating that a static sampling strategy severely influences efficiency; 2) static sampling entails long measurement time; large environmental change produces large errors in distance measurement, an effect that directly diminishes the accuracy of surface measurement. Errors caused by environmental change can be eliminated using compensation methods, but such approaches are complicated to carry out[5,6]. To solve these problems, we propose a scanning sampling strategy for measuring large optical surfaces.

The specifications of laser tracker coordinate measurement machine are insufficiently accurate for optical surface measurements at fine grinding[7]. Most large optical mirrors are concave and their surfaces are similar to spherical surfaces—geometrical features that can be used to improve measurement accuracy.

As indicated by its working principle, a laser tracker can more accurately measure radial coordinates than angular coordinates. If we use DMI to get the normal direction information of surface and use angle encoders to get tangential direction information, high measurement accuracy could be achieved. In a parabolic mirror, for instance, if the laser tracker is placed at the mirror axis above the surface (Fig. 1), then

$$x = r\sin\theta, \tag{1}$$

$$z = H - r\cos\theta, \tag{2}$$

where R is the radius of curvature (RoC) of the mirror, H is the vertical distance between the laser tracker and mirror.

Incorporating Eqs. (1) and (2) in a parabolic function enables the derivation of the sensitivity of measured distance r to angle θ as follows:

$$\mathrm{d}r/\mathrm{d}\theta = \frac{r\sin\theta(R - r\cos\theta)}{r\sin\theta\sin\theta + R\cos\theta}, \tag{3}$$

and surface measurement error E caused by angular error $\Delta\theta$ is

$$E \approx= \frac{r\sin\theta(R - r\cos\theta)}{r\sin\theta\sin\theta + R\cos\theta} \times (\cos\theta + k\sin\theta) \times \Delta\theta, \tag{4}$$

where k is the slope of the contact point. Assuming that an $f/1.5$ mirror is being tested. The deviation caused

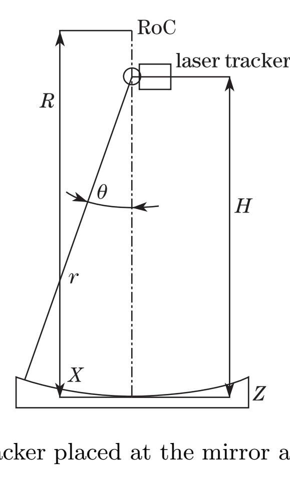

Fig. 1. Laser tracker placed at the mirror axis above the surface.

by the angular error at the edge is $0.002r\Delta\theta$ when the tracker is placed at the RoC of the mirror. Thus, the major error source is avoided.

The distance change at nanometer level can be measured using DMI alone, but measurement accuracy is strongly influenced by the environment. 1-°C temperature change over 1 m produces 1-μm error because of changes in the air refraction index. Thermal expansion and relative motion of the support also considerably contribute to the distance measurement error. In most cases, environmental change is related to measurement time. Figure 2 shows a typical environmental change in an optical shop over 3 m for 20 min measured by DMI (with the DMI equipment facing a fixed retro-reflector 3 m away; the related distance change is recorded). 12-μm environment error causes ineffective laser tracker measurement at fine grinding (Fig. 2).

The scanning mode of laser tracker samples dynamic SMR coordinates instead of the average coordinates of static SMR, making this mode relatively fast with high sampling density[8]. Nevertheless, the accuracy of angle measurement under this mode is low because of limited tracking speed. The specifications of a laser tracker do not cover dynamic angle measurement accuracy, which is tested with a precise rotary table.

A laser tracker is installed on a precise rotary table and SMR is fixed at 3 m away (Fig. 3). The rotary table rotates and the laser tracker tracks SMR and measures coordinates. If no angular measurement error is produced by the laser tracker, the collected coordinates can be fitted to an ideal plane, thereby we can get the angular error of each measurement points from their flatness deviations.

Figure 4 shows the static and scanning calibration results for the angular errors of the laser tracker. The scanning angular error is 1.5 times the static angular error. As indicated in Eq. (2), scanning sampling negligibly affects the accuracy of surface measurement when a laser tracker is placed at the RoC of a mirror.

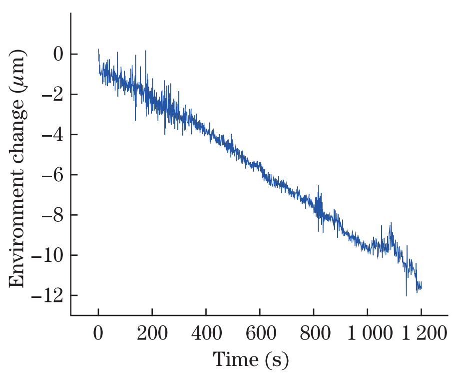

Fig. 2. Typical environmental change in an optical shop.

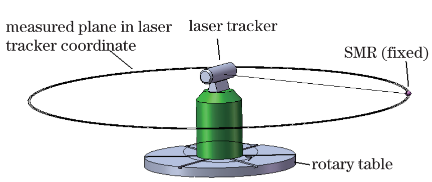

Fig. 3. Rotary table used to calibrate the angular error of the laser tracker.

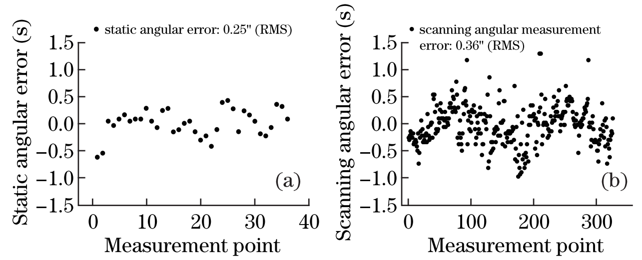

Fig. 4. Results of (a) static and (b) scanning angular error calibration.

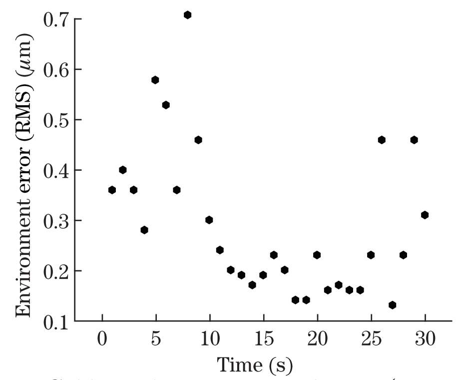

Fig. 5. Calibrated environmental error (30 times).

A Φ 1.3-m parabolic mirror is measured using the laser tracker, which is placed at the RoC of the mirror; 16 radial lines are measured. The analysis of uncertainty in scanning measurement reveals the following insights:

1) Measurement uncertainty from laser tracker u_l

The measurement uncertainties caused by the laser tracker include DMI error, axis wandering, thermal expansion, and SMR imperfection. We evaluate these uncertainties by measuring a Φ140-mm standard spherical mirror[9]. The obtained standard uncertainty of the root mean square (RMS) is 0.16 μm.

2) Measurement uncertainty from environment u_e

As stated above, variations in relative motion, vibration, air fluctuation, and refraction index produce measurement uncertainties. The uncertainties can be evaluated by using a laser tracker to continuously measure a fixed SMR. Figure 5 shows the RMS value of 30 environmental changes within 1 min at a sampling interval of 1 s. The standard uncertainty of the RMS is 0.33 μm.

The combined uncertainty of the measurement is 0.36 μm (RMS) and the expanded uncertainty (k=2) is 0.72 μm.

A total of 20 min is spent on static sampling mode and 320 points are collected; 1 min is devoted to scanning measurement mode and 1 760 points are collected. The measurement results are shown in Fig. 6.

The surface error of static sampling is large and irregular, whereas that of scanning sampling is more symmetrical and continuous—a finding that accords with that achieved by the fabrication technique[10].

The experimental results are compared with those obtained using a coordinate measurement machine (CMM),

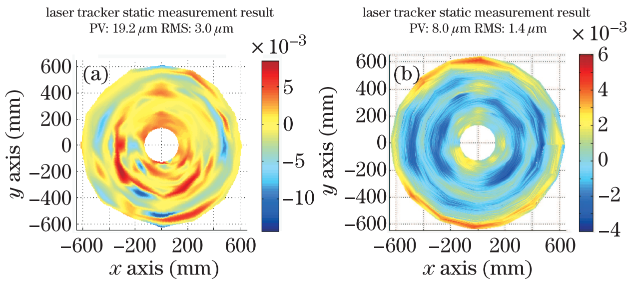

Fig. 6. (Color online) (a) Static and (b) scanning surface measurement results of the laser tracker.

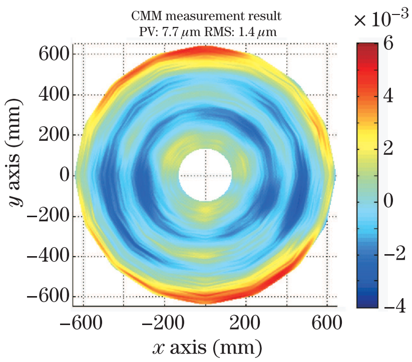

Fig. 7. (Color online) CMM surface measurement results.

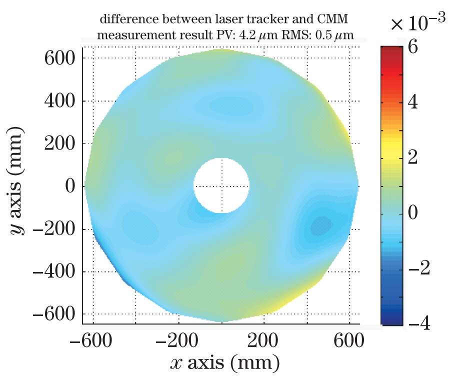

Fig. 8. (Color online) Deviation between laser tracker scanning and CMM measurements.

which entails 3 h for a collection of 1760 points. The accuracy of CMM is $(2.2+L/350)$ μm and its surface measurement uncertainty is 0.61 μm (RMS, obtained by measuring a polished mirror with close aperture). The results are shown in Fig. 7. The scanning measurement results of the laser tracker are 8.0 μm in peak-to-valley (PV) and 1.4 μm in RMS, respectively, and the CMM results are 7.7 μm in PV and 1.4 μm in RMS, respectively. The two surface shapes are also consistent.

Figure 8 shows the deviation between the measurements of the laser tracker and CMM. An experimental deviation of 0.5 μm (RMS) is within each uncertainty, demonstrating that the laser tracker can satisfy fine grinding requirements.

In conclusion, we present an approach to using a laser tracker to perform fast and accurate surface measurements for large mirrors. Using the scanning mode of the laser tracker enables the completion of surface measurement within minutes, considerably reducing environmental errors and increasing sampling density. With this method, we can obtain a surface measurement accuracy within 1 μm (RMS), which is sufficient to guide fabrication before polishing. Thus, the proposed method is a convenient means of manually measuring mirrors, particularly large ones.

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