COMPARISON OF TWO INSTRUMENT DESIGNS FOR NON-CONTACT MEASUREMENT OF GOSSAMER MIRRORS

Phil Smith and R. Ryan Vallance
Precision Systems Laboratory, University of Kentucky*

Abstract

Lightweight, large format mirrors are planned for the next generation of space-based telescopes to collect the maximum amount of light from faint sources. A second, less-demanding application for large format mirrors is for the collection of solar radiation. In either case, accurate measurements of the large-scale form of the surface of gossamer optics must be achieved. If the wavelength of light is in the visible region, then a useful measure should have accuracy on the order of 50 nm or less to be a useful indication of the quality of the optic. In this paper two machine designs are compared and contrasted to determine which machine offers the potential accuracy, while allowing sufficient flexibility for measuring a variety of mirror surfaces and curvatures.

Keywords

membrane optics, gossamer optics, ultra-lightweight mirrors, non-contact form measurement

Introduction

The traditional method of measuring the form of large optics is using an interferometric method [1]. Optics divert a plane wave to the idealized shape of the optic, then the fringe pattern on the surface is checked for areas that need further work. In many cases, a CCD camera captures the image of the fringe pattern for analysis.

Unfortunately, this method is limited in the surfaces it can easily evaluate. Some optics may require a customized, holographic grating to check for form errors. For different radii of curvature, a different optic would be required. Large deviations from the ideal form cannot be measured interferometrically, due to the overlap of fringes. Often for this reason the interferometer method is used only at the final evaluation step.

Another method of surface evaluation is to use contact profilometry to measure multiple points on an arc [2]. A pivoting arm is designed to trace a circular arc, and a gauge measures deviation in radius from sphericity. To access all points on the surface, a second rotational axis is required, either to rotate the measurement structure over the mirror surface, or to rotate the mirror surface under the measurement structure.

The proposed machines is designed to have both the non-contact benefit of interferometer techniques, as well as the flexibility of pivoting arms provide to measure a variety of near-spherical shapes with a minimum of specialized optics or extended setup.

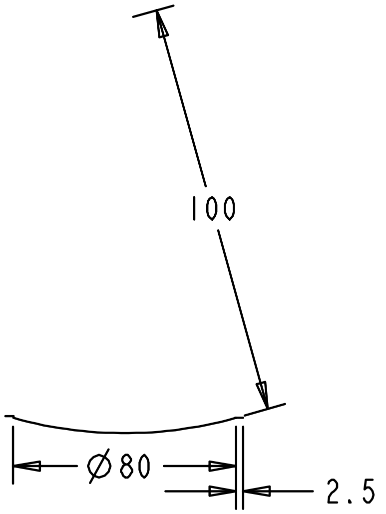

Figure 1. Initial target values for mirror dimensions, in mm

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[*] *Precision Systems Laboratory, Mechanical Engineering Department, University of Kentucky, Lexington, KY 40506. http://www.engr.uky.edu/psl.*

Mirror Description

The initial target mirror dimensions for this application are shown in Figure 1. The surface has a radius of curvature of 100 cm and a diameter (circumference/pi) of 80 cm. The mirror is formed from a thin sheet of polymer with aluminum deposited on the concave side.

As with most gossamer optics, the mirror is designed to be supported only by its edges, so a “nest” has been designed that allows for uniform support of the edge of the mirror. The nest also has a series of holes around its upper surface that provide a slight vacuum to hold the film in place during measurement. This nest is shown in Figure 2. The mirror must be mounted horizontally to prevent it from collapsing under its own weight, due to lack of any significant stiffness of the polymer. Naturally, such a flexible surface can only be measured using a non-contact method. Since the mirror surface is aluminized, a capacitance gauge is chosen as the optimal non-contact sensor to be mounted on the end of the probe tip.

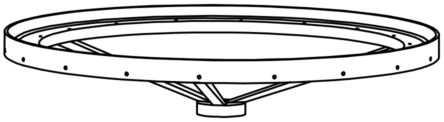

Figure 2. “Nest” for supporting thin flexible mirror

Radial Displacement Sensing

The proposed device for non-contact measurement of the mirror surface is a capacitive gauge sensor. These sensors have the advantage of an averaging effect over the active area of the sensor (typically ~2 mm^2), thus averaging out roughness and waviness wavelengths. This size is also compatible with the number of measurement points desired for analysis purposes.

Although a capacitive gauge such as that proposed herein can detect relatively large changes in distance (1 mm or more on lower sensitivity settings [3]), this extended range comes at the expense of a loss in resolution. It is proposed instead that the cap gauge be mounted on a small air bearing and kept at a constant distance from the surface using a voicecoil or linear motor and closed-loop feedback. This arrangement will also prove advantageous when analyzing systematic errors. The movement of the capacitive gauge in the radial direction will be measured by a laser interferometer. A similar scheme has been proposed previously using a commercially available CD optical head [4], but this does not have the averaging advantage provided by the capacitance gauge.

The primary limitation of standard commercial capacitance gauges is in the range of acceptable angles. Because of the small gap and relatively large flat surface (including guard ring structure), the maximum angle of one commercial gauge is calculated to be ~ 2.3 degrees at the highest sensitivity setting. Ultimately this range limits the mirror geometries that can be measured, and highlights the importance of proper alignment when setting up this machine.

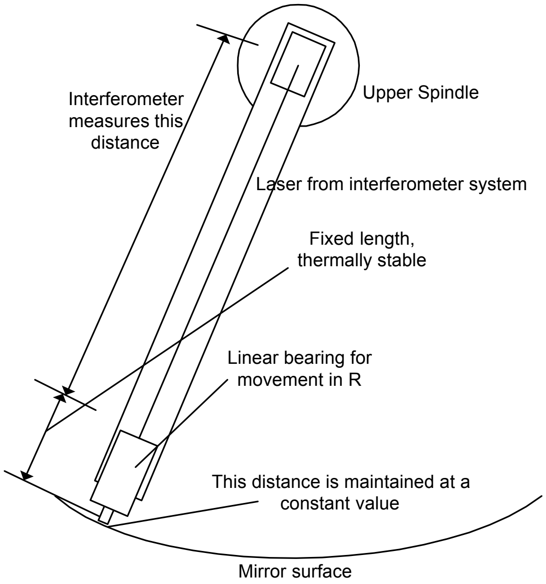

Figure 3. "Pendulum” design

Two Competing Instrument Designs

The first instrument design considered for this measurement uses a “pendulum” geometry, with a radial arm pivoted at the nominal center of the mirror. The basic configuration of this system is shown in Figure 3. The nest is supported by a spindle that allows rotation around a vertical axis. The pendulum pivots on a second, horizontal axis to sweep across the surface of the mirror. The light path for the interferometer travels along the horizontal axis of the upper spindle, then is reflected downward to the back side of the capacitance gauge sensor. For a perfectly spherical mirror with the upper axis of rotation intersecting the center of the mirror, the variation in radius and the tilt of the surface are naturally both zero.

The second design considered for this machine uses a "swingarm" to traverse the surface of the mirror. This design is shown in Figure 4. As in the first machine, the mirror is mounted horizontally on a rotating spindle. For optimal operation of the machine the tilted axis of the swingarm must intersect with the vertical axis of the mirror at the nominal center of the mirror.

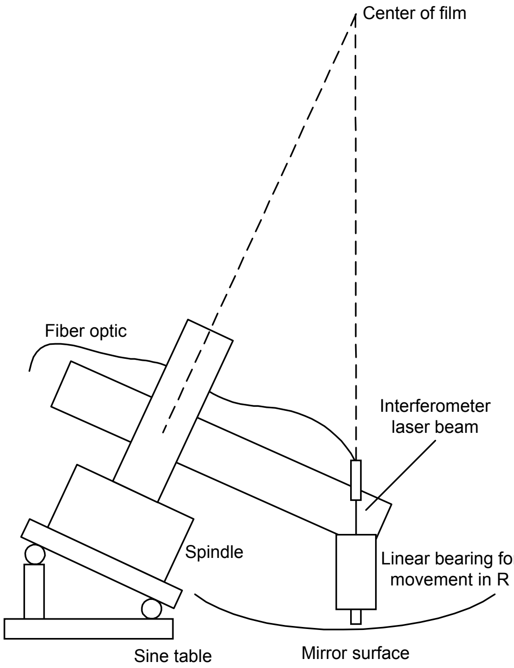

Figure 4. "Swingarm" design

First Design: The "Pendulum"

The pendulum design shown in Figure 3 is the most straightforward of the two designs. The upper spindle supports a stiff but lightweight arm that in turn supports the linear bearing and voicecoil. This spindle is mounted in a large overhead structure, possibly granite, which allows for multiple mounting locations of this spindle.

The laser for the interferometer passes through the center of this spindle, then is reflected downward, along the arm, to the back side of the capacitance gauge mount. This mount is to be made of zerodur or a similar low CTE material. The advantage of this light pathway is in its ability to include changes in the length of the overall arm due to gravity, temperature changes, etc. Temperature changes may affect the surrounding granite structures, but they have a much more significant thermal mass.

A final point in favor of this design is in the ease of calculating the angular location of the surface points. Figure 5 shows a plot of lines traversed by the capacitance gauge. For a given measured point it is only necessary to read the two angles from the two spindles. These angles, combined with the radius determined by the interferometer, specify the exact location in space of that point on the mirror.

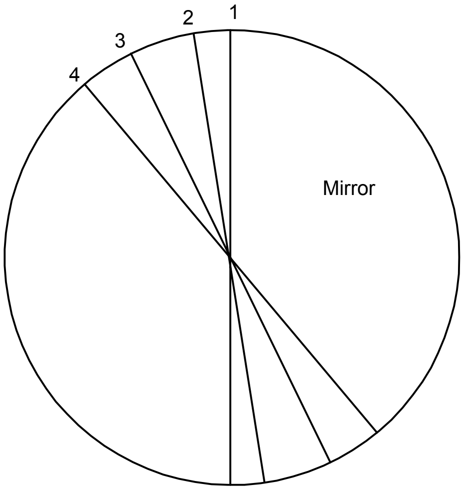

Figure 5. Downward-looking plot of lines traversed by pendulum design

The most fundamental limitation of the pendulum design is its inability to measure a wide range of different curvatures. Since the upper spindle must be aligned with the nominal center of curvature of the film, relatively flat mirrors require mounting the spindle high above the surface. Any offset between the spindle and this center results in added tilt between the capacitance gauge and the surface. A sample plot of this increase is shown in Figure 6.

As the radius of curvature of the mirror increases, the length and mass of the arm increases, with a third-order increase in the bending angle of the arm. Even given multiple mounting locations for the upper spindle, the final alignment must be achieved by raising/lowering the film, necessitating z-axis motion of the lower spindle. Alignment of the center of the film under the zero position of the pendulum arm requires x and y axis control of the lower spindle as well.

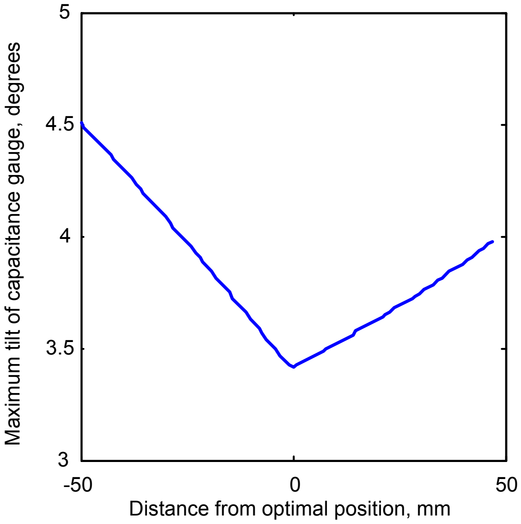

Figure 6. Tilt angle due to spindle offset from film center, pendulum design

Second Design: The "Swingarm"

The swingarm design of Figure 4 uses a different geometrical configuration to position the capacitance gauge over different points on the mirror surface. In this case a horizontal arm rotating on a tilted axis suspends the capacitance gauge mount above the surface. The capacitance gauge is moved in the radial direction by the same voicecoil arrangement described above. As can be seen from the figure, a huge advantage to this system is that the arm is only slightly larger than the radius of the mirror. For different radii of curvature, only the angle of the sine table changes. This geometrical relationship is given [2] by the equation

$$\sin\theta = \frac{L}{R} \tag{1}$$

Where L is the perpendicular distance from probe tip to axis of rotation, and R is the nominal radius of the film. Once the approximate angle is set by adjusting the sine table, the mirror is moved to its final position using x and y axes. No z-axis motion of the mirror is required for alignment. As can be seen from the above equation, the swingarm design can even accommodate a mirror of infinite radius (flat surface). Finally, since this design locates the measurement equipment to one side of the surface, other equipment (e.g., optics) can be mounted overhead.

One downside of this swingarm arrangement is the difficulty in choosing the optical path for the interferometer. Current thinking is to bring the laser to the end of the arm using fiber optics, measuring just the travel of the capacitance gauge relative to the end of the arm. No longer can the laser pathway measure all vertical motions of the capacitance gauge mount. Instead, corrections due to arm bending and thermal drift must be added later, as described in the systematic errors section.

A second difficulty arises when calculating the location on the mirror surface of measured points. As can be seen in Figure 7, rotating the capacitance gauge causes arcs to be traced on the surface of the mirror. The position of these points is calculated from knowledge of the distance L of the machine and the angular information from the two spindles.

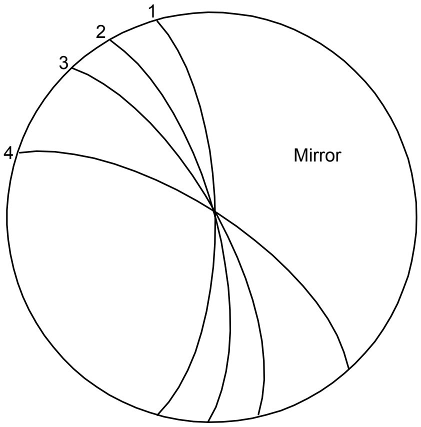

Figure 7. Downward-looking plot of arcs traversed by swingarm design

Systematic Errors

Several systematic errors of this machine are anticipated and are being analyzed. The temperature of the various parts of the machine changes the dimensions slightly; in both designs some of these changes will be in the sensitive direction. Once the measurement time is known (the number of minutes necessary to measure an entire surface) room temperature fluctuations over this time scale can be evaluated.

A second systematic error occurs whenever the capacitance gauge is tilted with respect to the surface being measured. The capacitance gauge is factory-calibrated using a parallel reference flat at a known distance. Any tilt with respect to the surface being measured has the effect of the capacitance gauge perceiving the average distance as being closer than it actually is. Closed-form solutions to this capacitance problem exist for small angles [5], one such solution is as follows:

$$C = \frac{2\pi\varepsilon r^2 \cos\theta}{d_0}\left[\frac{1-\left(1-k^2\right)^{0.5}}{k^2}\right] \qquad (2)$$

$$k = \frac{r\sin(2\theta)}{2d_0} \qquad (3)$$

The plot in Figure 8 shows the percentage error in distance for a particular spacing and tilt angle. This correction can be added to radius values from either machine by simply calculating the gradient of the surface at each measurement point, then adding the appropriate value.

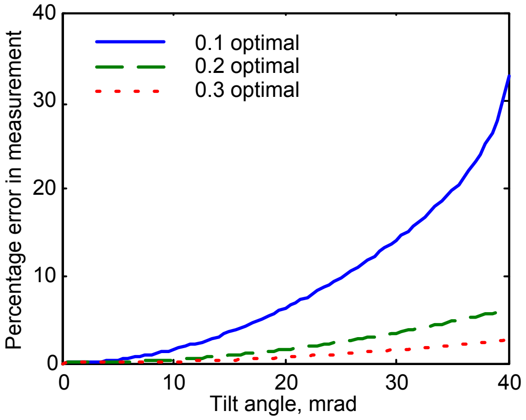

Figure 8. Plot of distance offset as a function of tilt angle, optimal spacing in mm

Another systematic error is due to structural bending or extension of the measurement arm. As discussed previously, in the pendulum design the extension of the arm is included in the measurement of the R value by the interferometer. At any position other than vertical there also exists bending in the arm, which is manifest in both deflection and tilt at the end of the arm. Tilt errors are most likely much smaller than the tilt encountered by the cap gauge simply due to the mirror surface being aspheric. Equations for deflection can be solved as a function of the arm angle, and these can be used to correct the location of the measurement point in postprocessing.

For the swingarm design, the arm is primarily in a bending mode, although the direction changes as a function of both sine table and spindle angle. For this reason it is advisable to use a hollow cylinder as the arm structure, since this geometry has a uniform moment of inertia for bending at any angle. As above, changes in capacitance gauge position as a function of angle can be added in postprocessing.

Setup and Measurement

The resolution goal of measurements along the surface of the mirror is 0.1 mm in any direction. To achieve this the arm must be set to zero and the mirror centered under this arm. All measured distances and angles will be from this point, so this alignment is crucial.

The first step in this alignment is the x-y adjustment of the mirror relative to the capacitance gauge. For this purpose a reference surface is ground into the nest holding the mirror. Checking the distance to the reference surface when the arm is at $\pm\theta_{\max}$ ensures that the film is centered in the x and y directions.

The second step in this alignment is to locate the center of the mirror. To a certain level this can be done visually by spinning the mirror continuously and moving the capacitance gauge to the proper location. Next, the capacitance gauge is held fixed and the analog output voltage (proportional to distance) is viewed over time. When the mirror is exactly centered, the voltage of the gauge will be minimized. Since these two steps are somewhat dependent on each other, they may have to be repeated for optimal alignment.

Parametric Studies

To study the geometry of the swingarm model in greater detail, a skeleton model of the structural components was created in ProEngineer. This model, shown in Figure 9, was used to perform sensitivity studies as the arm traversed the surface. First, a spherical surface was created and the probe swept across its surface. As expected, with optimal alignment the probe surface remained equidistant and parallel to the mirror surface at all angles. Of greater interest is the clearance of the main arm with respect to the edge of the film, as plotted in Figure 10. This information is helpful when designing the arm and nest structures.

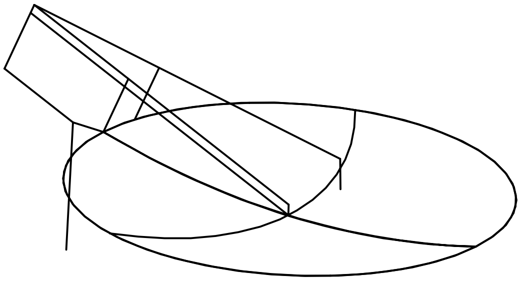

Figure 9. Skeleton model of swingarm design for parametric studies

A second study modeled a parabolic mirror surface with similar dimensions to the original, spherical surface. Figure 11 shows the radial travel such a surface would necessitate. This information is essential when designing the capacitance gauge support structures.

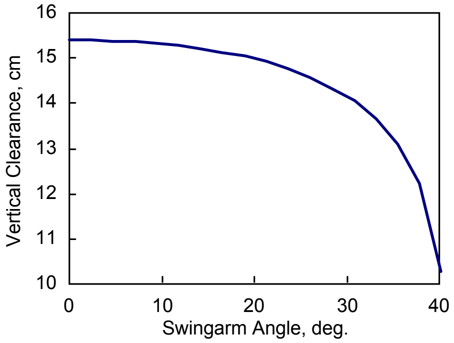

Figure 10. Clearance of swingarm over mirror edge as a function of arm angle.

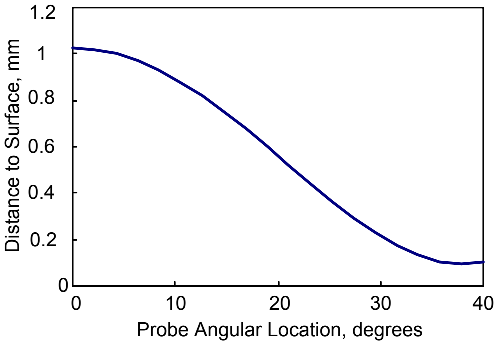

Figure 11. Travel distance required for probe for parabolic surface

Conclusions and Future Work

The swingarm design has been favored to this point due primarily to its greater flexibility in measuring a variety of surface curvatures and to its shorter arm length. Also, the lower profile of the equipment makes this design more easily built from existing machine structures. A solid model is shown in Figure 12.

A final decision on which design will be built and tested must wait until a complete error budget analysis is performed. Already it is apparent that the machine precision will be greatly affected by the choice of rotational bearings. It is likely that the final design will incorporate one or two air bearing spindles, selected for their low radial, axial, and tilt errors.

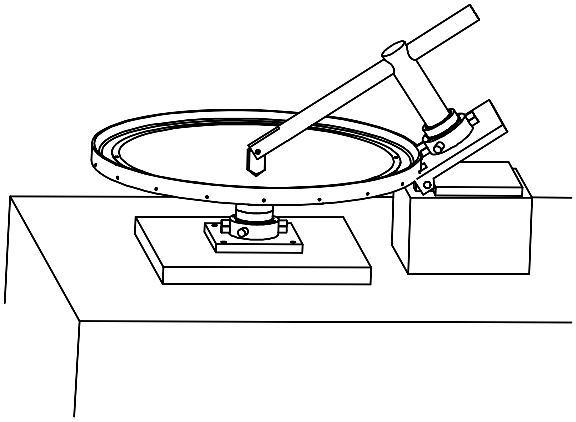

Figure 12. Solid model of final design

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