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Karlene Karrfalt, Robert E. Parks, Daewook Kim, "Evaluating SMR positioning with an autostigmatic microscope," Proc. SPIE 12221, Optical Manufacturing and Testing XIV, 122210Y (3 October 2022); doi: 10.1117/12.2633238

SPIE.

Event: SPIE Optical Engineering + Applications, 2022, San Diego, California, United States

Evaluating SMR Positioning with an Autostigmatic Microscope

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ABSTRACT

An optical method of determining the location of the apex of a corner reflector mounted in a steel ball, commonly referred to as a Spherically Mounted Retroreflector (SMR), relative to the center of the ball to the 1-2 μm level was previously described by us. The method used an autostigmatic microscope focused on the apex and viewed the reflected spot image as the SMR was rotated about a normal to its entrance aperture. This measurement determined the lateral offset of the apex and tipping the SMR while viewing the spot gave an indication of the axial displacement.

A related questions arose recently, could the distance between two SMRs be determined to the same level of precision if the SMRs were rigidly mounted in a fixture so they could not be moved. We show the answer is yes assuming the stage moving the pair of SMRs has the required precision. As a SMR is scanned under the autostigmatic microscope the spot motion seen by the microscope is identical to that seen when scanning a spherical ball under the microscope and we have already shown that balls centers can be found to 1 μm precision using a 10x objective.

We show experimentally that we can determine the distance between 2 SMRs by repeated measurements with the balls in different azimuthal orientations, and show that by taking into account the orientation, the distance between SMRs remains the same within experimental errors.

Keywords: Spherically mounted retroreflector, SMR, Point Source Microscope, PSM, Autostigmatic Microscope

1. INTRODUCTION

The motivation for this paper was a question about calibrating a fixture, for what we think was a laser tracker, that used two spherically mounted retroreflectors (SMR)s spaced a precise distance apart[1]. As the result of another inquiry[2], we knew we could locate the vertex of the cube corner reflector in a SMR with a Point Source Microscope (PSM)[3], discussed in Section 2, by rotating the SMR in its kinematic locating nest[4]. In the case of the fixture calibration, the SMRs could not be rotated so the question became, could we find another method to measure the distance between apexes of the two SMRs.

Much before this time we had used the PSM to measure the distances between the centers of a row of precision balls pressed tightly against each other. By scanning the PSM across the row of balls while it was focused at the level of and in line with the centers of the balls, we could determine precisely when the PSM was centered over the balls in the scan direction. In this way we could determine the distance between the centers of the row of balls. Based on the paper written about finding the apexes of the cube corners in SMRs, we realized that scanning across a SMR would yield the same response from the PSM as if we were scanning solid balls. This paper is a documentation of that experiment.

We will first briefly describe the PSM used in both measurements and then show the previously unpublished results of scanning across the row of touching balls to demonstrate the method. Then we show the results of scanning across a ball and an SMR in the x and y directions in order to locate the ball and SMR centers. Finally we show the results of scanning across pair of SMRs to demonstrate the same kind of result as scanning across the solid balls. The main difference between the two cases was that the scan across the solid balls was a continuous motion with data being taken every 20-40 μm of scan while the measurement of the SMRs was done by manually moving the SMRs under a stationary PSM and taking data at a limited number of points.

Optical Manufacturing and Testing XIV, edited by Daewook Kim, Heejoo Choi,
Heidi Ottevaere, Proc. of SPIE Vol. 12221, 122210Y · © 2022 SPIE
0277-786X · doi: 10.1117/12.2633238

Typical results of the two types of scans are shown to substantiate that the scans yield the same type of data. The data from the SMRs are better than the continuous scan of the solid balls because the data were taken carefully to prove a point while the solid ball scans were done to show feasibility of the method. We give an analysis of the SMR data to show the precision expected from similar SMR measurement as well as a couple of tips about how to make the measurements.

2. BACKGROUND

2.1 Autostigmatic microscope

The data taken for the solid ball and SMR scans were collected using a Point Source Microscope (PSM). A PSM is a classical autostigmatic microscope[5] equipped with a single mode fiber pigtailed to a laser diode as the source and a digital camera to view the reflected images from the centers of curvatures and apexes of the optics being measured. Another key distinction of the classical autostigmatic microscope (ASM) is that internally it uses collimated light in the vicinity of the beam splitter. This means that when the microscope objective is removed, the PSM is an autocollimator as seen in Figure 1. Another way of thinking about the PSM is that it is an autocollimator with an objective so its focuses at a finite distance.

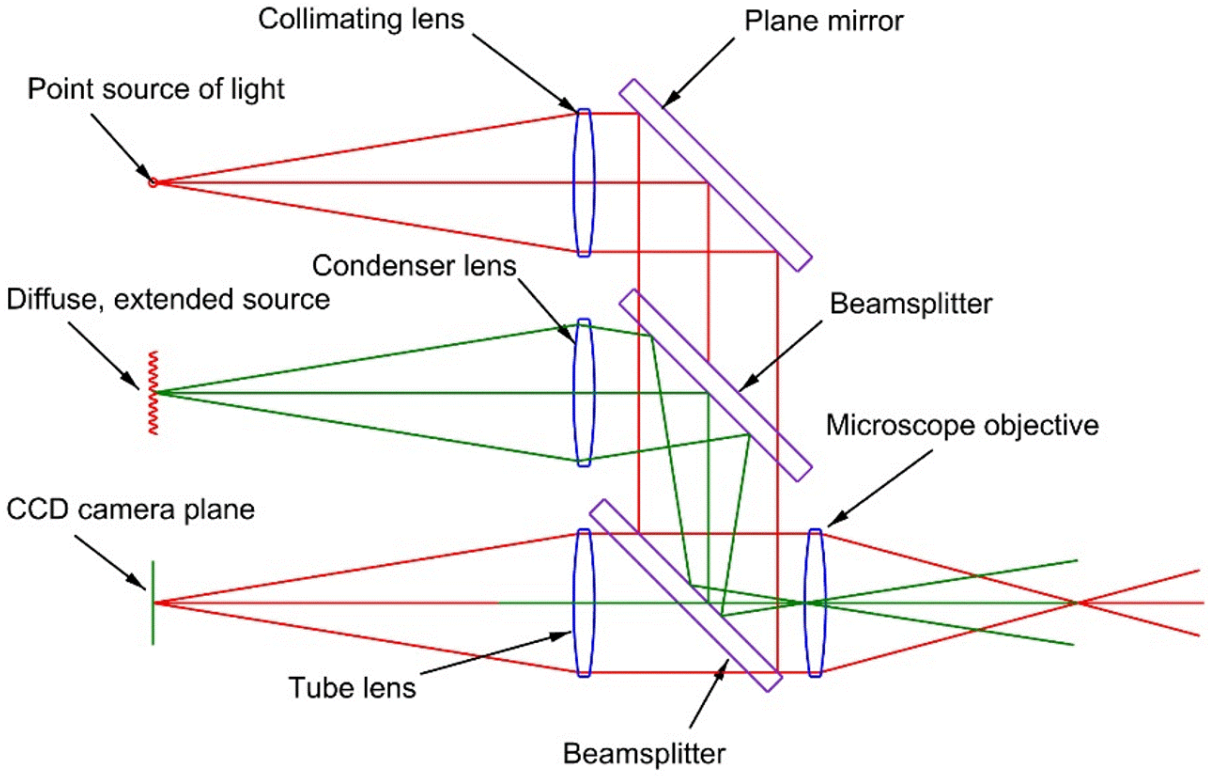


Figure 1. Optical ray paths in the PSM with the removeable microscope objective that converts it to an autocollimator.

The classical use of an ASM is the measurement of radii of lenses and mirrors. The ASM is first focused on the surface of the lens or mirror to get a Cat's eye image. This focus establishes where the mirror surface is and is used to establish the origin pixel on the digital camera in the PSM because even if the surface is slightly tilted relative to the axis of the PSM, the reflected light spot always lands on the same origin pixel of the camera because that pixel is also conjugate with the fiber source and the image of the source on the mirror surface. Note also, when the fiber source is imaged on the surface, only one ray hits the surface at normal incidence. Rays in the light cone exiting the objective at the top of the aperture are reflected back through the bottom because the angle of incidence equals angle of reflection.

After focusing the PSM on the surface of the optic, the PSM is then moved away from the mirror, in the case of a concave mirror, to a point where the focus of the objective is near the center of curvature. The PSM is move in x, y and z until there is a well focus return spot on the origin pixel of the camera. In this condition, every ray in the cone of light incident on the mirror from the objective focus at the center of curvature is normal to the surface of the mirror.

As the PSM is moved one unit in x or y from the center of curvature the reflected spot moves 2 units on the PSM camera as seen in Figure 2. This means that as the PSM scans across the ball the reflected spot appears to move twice as fast as the scan speed. Figure 2 also shows the case for scanning the PSM past a hollow 90° prism, an analog for a cube corner that is easier to draw in 2 dimensions and behaves from the PSM vantage point the same as a hollow cube corner. Again, the reflected spot moves twice as fast as the scan. The behavior of the reflected cone of light in the two cases is different in that the cone rotates when reflected from the ball but decenters without rotating from the cube. This is exaggerated in Figure 2 for clarity. In practice the difference is small since the shifts in both cases are at most a fraction of the mm of decenter. When you think about the shift in terms of object height it is clear the effect is the same on image height at the camera.

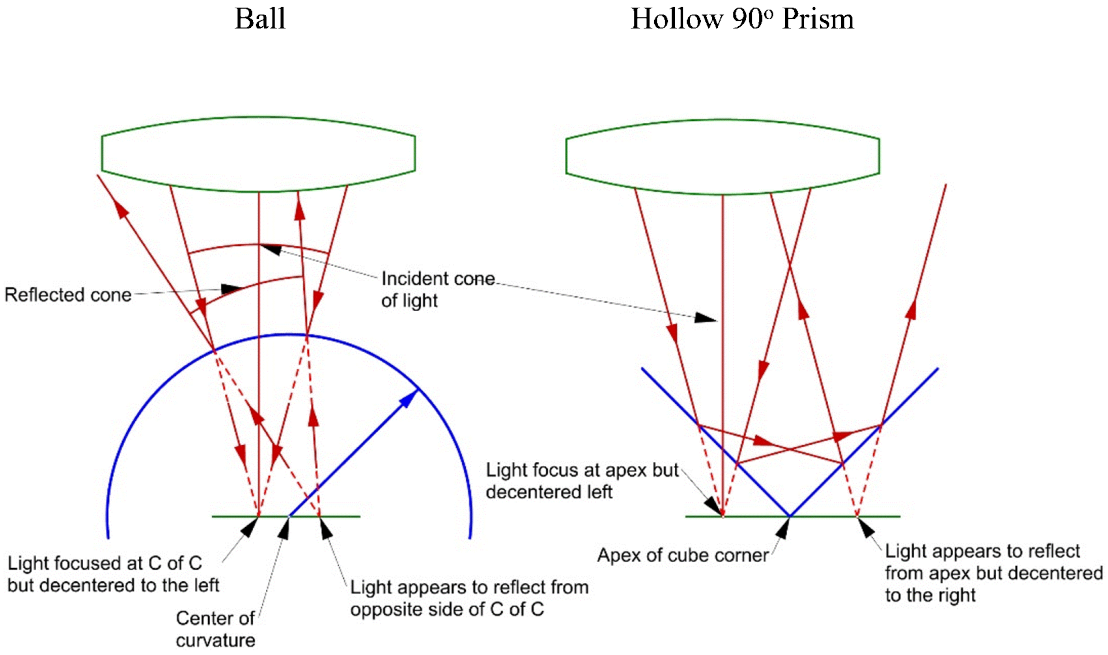
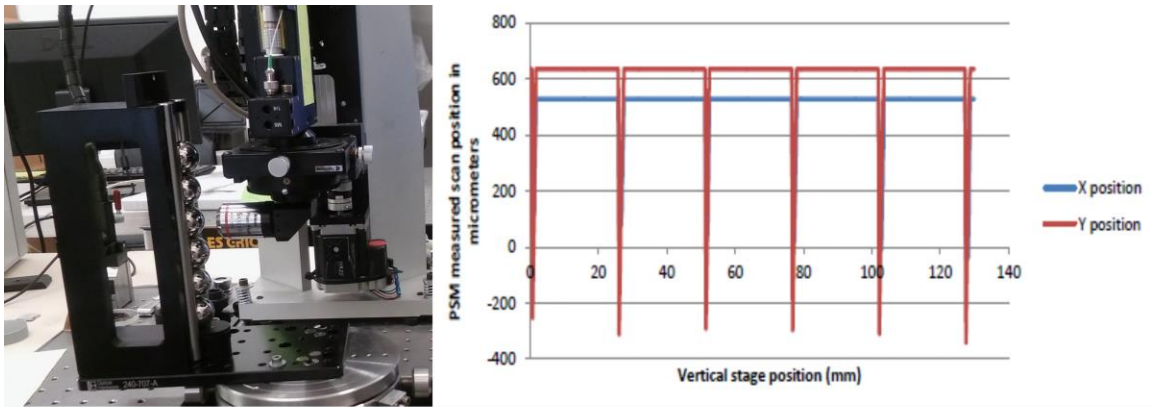


Figure 2. The effect of decentered cones of light incident on a ball or hollow 90° prism on the reflected cones.

2.2 Opto-mechanical alignment and measurement with an autostigmatic microscope

Some years ago, Roberts Parks did an experiment where aPSM was continuously scanned over a row of 1" diameter, Grade 5 balls. The balls were constrained to lie in a straight line and positioned so that they touched each other. The experimental set up is shown in Figure 3(a). The vertical row of balls are on the left of the setup. A right angle fold mirror was used on the PSM so the objective was facing the balls.

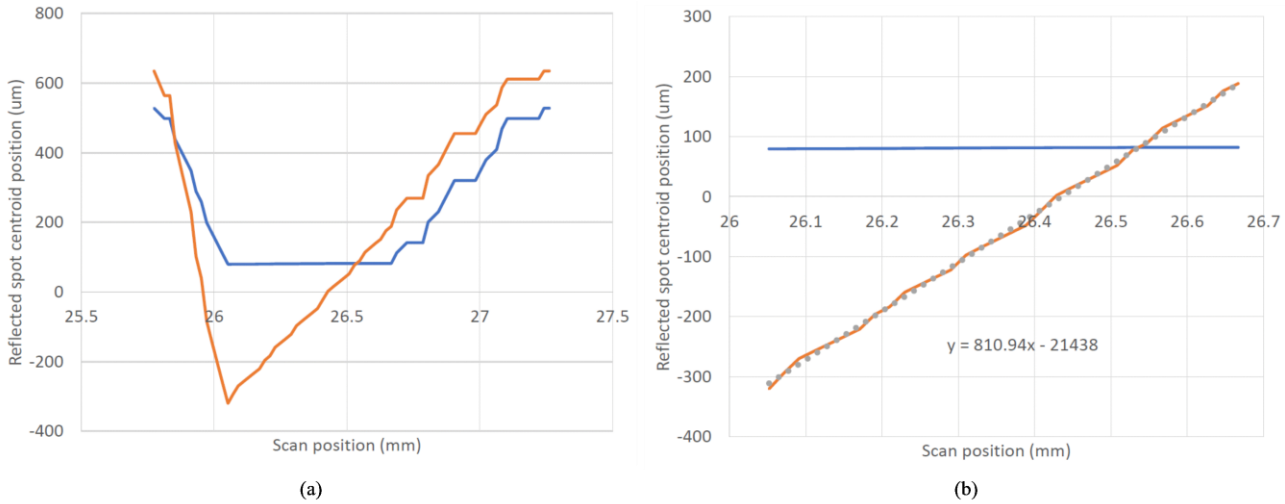
This experiment was done simply to show the feasibility of doing a continuous scan over a row of balls but is useful for introducing the similar concept of scanning over a set of SMRs. Figure 3(b) shows the PSM data output where ball center of curvature locations was sampled in intervals between 20 and 40 µm apart over the slightly more than 125 mm distance between the outer most ball centers. The red curve shows the ball center locations in the scan direction. Obviously, no light got to the camera except very near the ball center so the data around 630 µm is dead time in the scan. The ball centers are the spikes in the -300 µm region. The blue curve is the ball center in the cross scan direction. The visible part of this data at about 540 µm is dead time and the actual ball center data is hidden behind the orange curve.



(a) (b)

Figure 3. (a) (left) Ball scanning experimental setup. (b) (right) Data from the scan over the row of balls.

Figure 4 shows a 2 mm portion of the scan over the 2nd ball in the row. At about 25.8 mm along the scan light starts getting into the objective so the PSM centroiding algorithm tries to find a centroid. It is not until 26.1 mm or so, however, that a good image is found which tracks across the camera in a way expected from the rays in Figure 2. At approximately 26.7 mm the light is moving out of the microscope objective and the centroiding moves to dead time. In the interval between 26.1 and 26.7 mm the centroid crosses the origin (0 mm) of the PSM camera in the scan direction (orange curve). The cross scan position of the centroid (blue curve) remains nearly constant at about 80 µm.

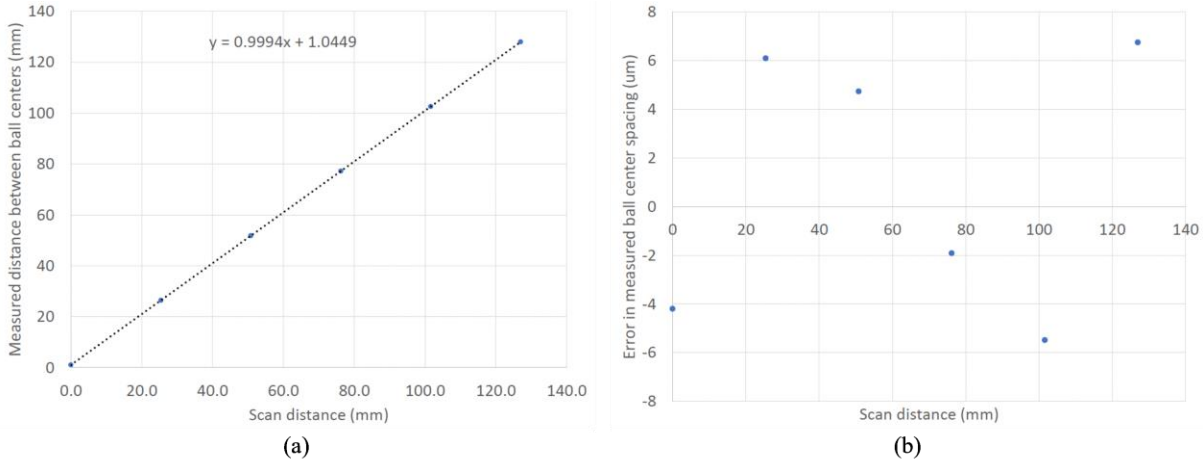


(a) (b)

Figure 4. (a) (left) Reflected spot centroids in scan (orange) and cross scan (blue) positions versus scan position. (b) (right) Linear fit of spot centroid in scan (orange) and center portion of cross scan (blue) positions versus scan position (blue).

If we look just at the portion of the scan in the vicinity of the origin, we see there is no data precisely at the origin but that the centroid moves linearly. This enables one to extrapolate the zero crossing as 26.436 mm. We can then use the scan direction zero crossing to solve for the cross scan centroid position at that same instant from a linear fit to the cross scan data to get a ball center of 81 µm.

The result of scanning all 6 balls where the zero crossing was calculated as described above is shown in Figure 5(a). The rather uninteresting Figure 5(a) shows a scaling error that translates to about a 75 µm error over the 125 mm scan that is probably in the leadscrew of the stage.



(a) (b)

Figure 5. (a) (left) Measured distance between ball centers versus scan distance. (b) (right) residual error in measured ball spacing after removing the best linear fit.

There was little error in the balls themselves as they were Grade 5, that is, within their nominal 25.4 mm diameter to 125 nm. Figure 5(b) shows the residual error in ball centers after removing the linear fit in Figure 5(a). This error is about ± 6 µm with the balls on the ends of the row the worst offenders. As stated above the data were taken at intervals of 20 to 40 µm and the entire 125 mm scan took 2 minutes at a constant velocity. This explanation of scanning solid balls leads directly into scanning SMRs with the difference that the only data taken was while the PSM was over the roughly 12 mm aperture of the SMR.

3. EXPERIMENTAL SET UP

The remainder of the paper now shifts to our experiment which shows that one can find SMR center by employing a similar scanning technique as that described in Section 2. Our experiment was conducted in two parts. First it is shown that scanning with a PSM over a ball produces the same result as scanning with a PSM over a SMR in both the x and y directions. The x and y scan planes are shown in Figure 6(c). First part of experiment used one kinematic mount on two cross mounted digital micrometer stages.

Before scanning over the ball and SMR the PSM and translation stages needed to be aligned to each other. This was done by placing the ball in the kinematic holder and aligning the ball center to the center position of the PSM CCD camera plane. This was done by centering the reflected spot from the ball in a cat eye configuration to the center of the PSM. Once the ball was aligned to the PSM, the digital micrometer translations stages were zeroed.

Next, with the micrometer translation stages aligned to the PSM, the ball was then manually translated across the PSM in the x direction and the reflected centroid position was recorded by the PSM. Approximately 10 measurements were taken and the corresponding micrometer positions recorded. This scanning procedure was then repeated in the y direction. Then the ball was replaced by an SMR and the procedure was repeated. It is important to note that the correct calibration scale factor for the corresponding microscope objective needs to be applied to the PSM position data.

For the second part of our experiment, two kinematic mounts (SMR nests) were attached to an aluminum plate at a distance of approximately 24.6 mm. This set up is shown in Figure 7. The righthand position (ball 1) was aligned to the center of the PSM as in the first part of our experiment. The relative position between the right hand (ball 1) and left hand (ball 2) positions were then measured by positioning the focus spot of the objective at the center of the ball as was described in Section 2.1. Finally, the balls were replaced by two SMRs and the scanning procedure described earlier in this section was used to determine the x position of each SMR relative to the other

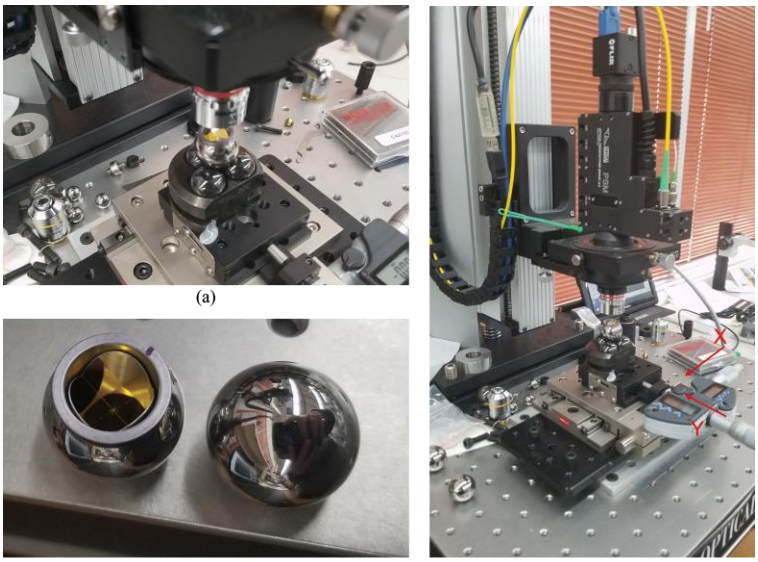


Figure 6. (a) (top left) SMR in kinematic mount. (b) (bottom left) close-up image of SMR (left) and sphere(right). (c)(right) PSM set up for SMR scan measurements. The x and y scan planes are shown in red.

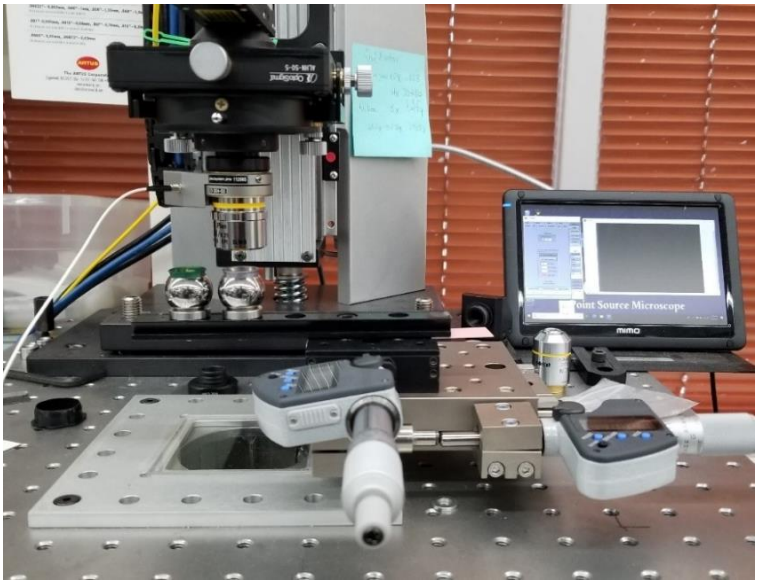


Figure 7 Set up for SMR relative position measurements. PSM was used to measure the reflected spot centroid from the scans of SMR 1(left SMR) and SMR 2 (right SMR)

4. EXPERIMENTAL DATA AND ANALYSIS

4.1.1 SMR position measurement

As was described in Section 2.2, the ball position of the PSM measurements were plotted against the micrometer scan position measurements in order to extrapolate the position of the ball and SMR. A linear fit was then applied to the data. The fit for the data is shown in Figure 8. In an ideal case one would expect the slope of the linear fit to be 2 as the reflected spot travels at twice the rate of the ball due to the reflected ray being at an angle twice that of the incident angle. From the

linear fit of the data one can see that the slopes are approximately -1.99. The deviation of the slope value from the ideal value can be attributed to the calibration factor of the PSM being off a little bit. The negative sign results from the positive direction of the micrometer scan being opposite to the scan direction of the PSM.

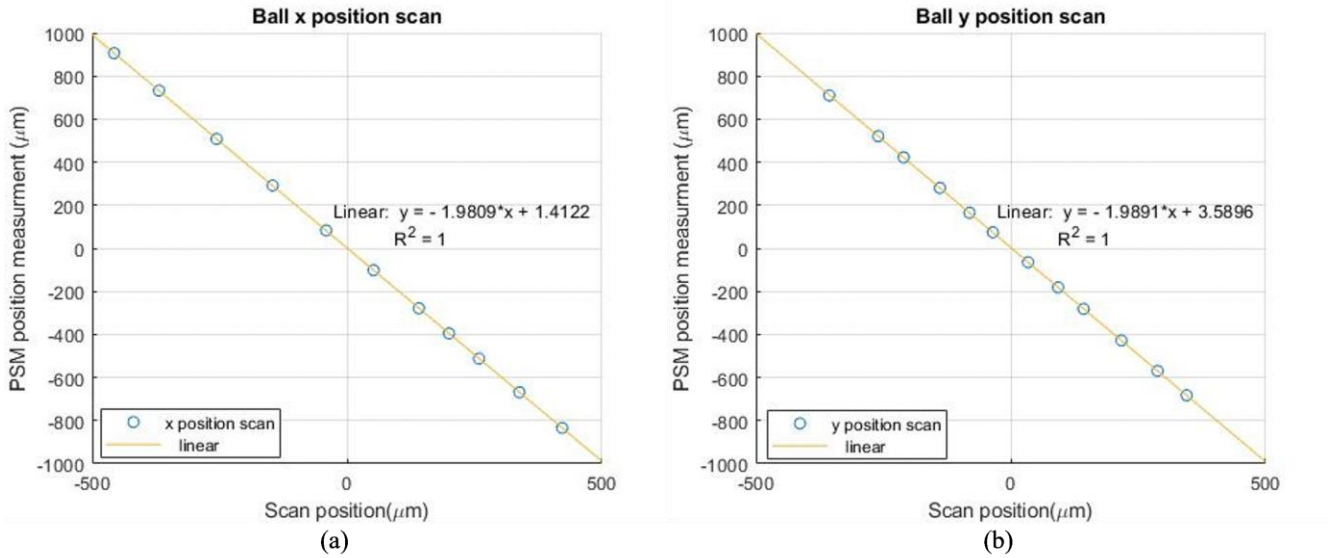


Figure 8. (a) (left) Ball x position scan and linear fit. (b) (right) Ball y position scan and linear fit.

The position of the ball center is then determined by solving the linear fit equation for the zero intercept of scan position axis. Using this method, the ball center is measured to be at x = -0.7 μm and y = -1.8 μm. This is within the accuracy expected for the spot centroid of the PSM.

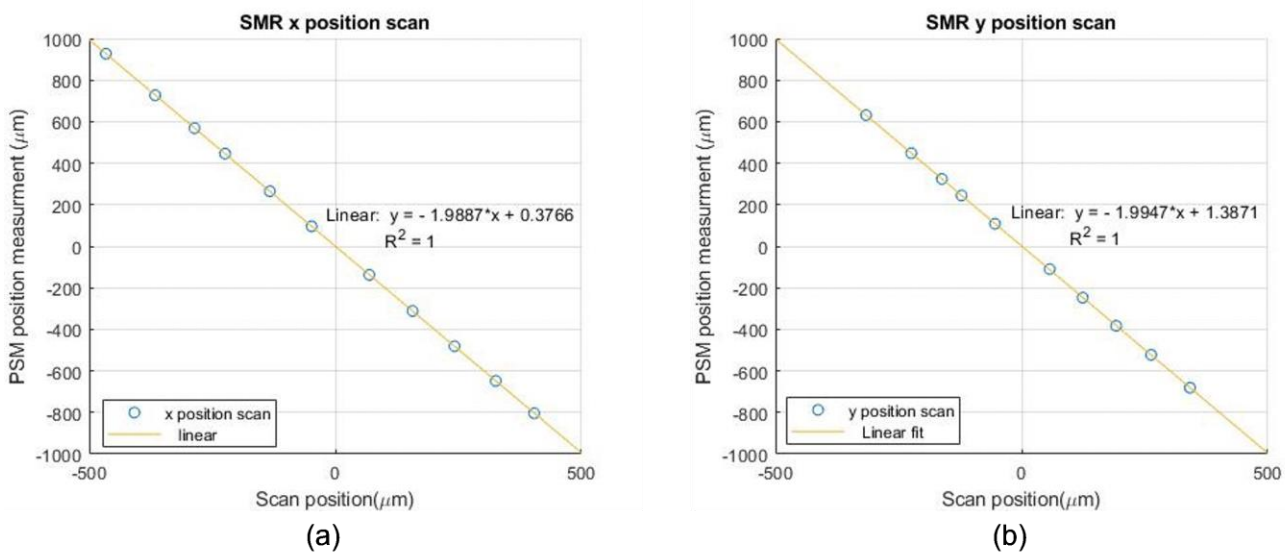


Figure 9. (a) (left) SMR x position scan and linear fit. (b) (right) SMR y position scan and linear fit

Next this procedure was then applied to the SMR scan data as shown in Figure 9. The SMR center is measured to be at x = 0.2 μm and y = 1.8 μm. Since both the ball and SMR were measured in the same SMR kinematic nest, the measured apex of the corner reflector must be corrected by the ball center measurement. The position of the ball and the SMR are also given in Table 1.

Table 1. Calculated position of the Ball center and SMR center in the x and y directions.

Center position	x (µm)	y (µm)
Ball	0.7	1.8
SMR	0.2	0.6

It is important to note that there may be a larger error in the scan of an SMR. These errors result from dust in the SMR as well as scanning along or across a joint in the retroreflector. It should also be noted that this technique will not be successful if on scans along the retroreflector joints. The joints disperse the beam rather than reflecting it preventing the linear data collection. An example of the retroreflector joints and dust in the SMR are shown in Figure 10.

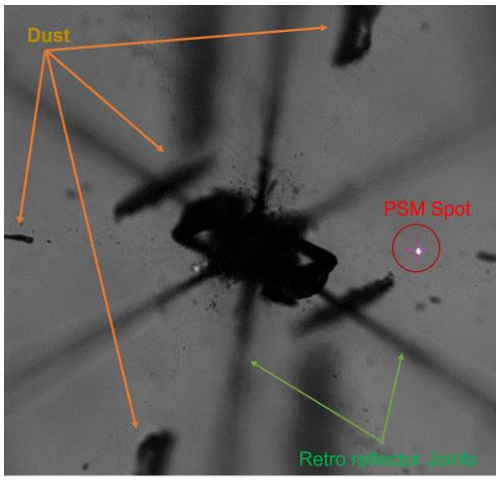


Figure 10. Image of dust and retroreflector joints in SMR. These two features can prevent accurate position scans and should be avoided whenever possible.

4.1.2 SMR relative separation measurements

As describe in Section 3, the ball positions were measured by the PSM using the focus spot of the objective positioned at the center of the ball. The corresponding positions on the digital micrometer stages were recorded. The x and y position of both spheres were measured 3 times each to determine the distance between the spheres. The measured positions are shown in Table 2 below. The average of the measurements was then taken. The difference between the measured position of ball 1 and ball 2 was taken to give a separation of 24.663 mm. This value is assumed to be our real separation value within the error of our experiment.

Table 2. Ball 1 and ball 2 center positions measured in a confocal configuration.

Measurement	Ball 1 (µm)	Ball 2 (µm)	Separation (µm)
Num. 1	13	24678	24665
Num. 2	14	24675	24661
Num. 3	13	24675	24662
Average	13	24676	24663

Next the spheres were replaced with two SMRs. The PSM was scanned across each SMR in the x direction and approximately 10 measurements were taken. Then as in the first portion of our experiment the PSM position measurements were plotted against the micrometer stage readings. The x position of the SMRs were determined by calculating the intercept of the scan position axis. The data and linear fit of the SMR position measurements are shown in Figure 11.

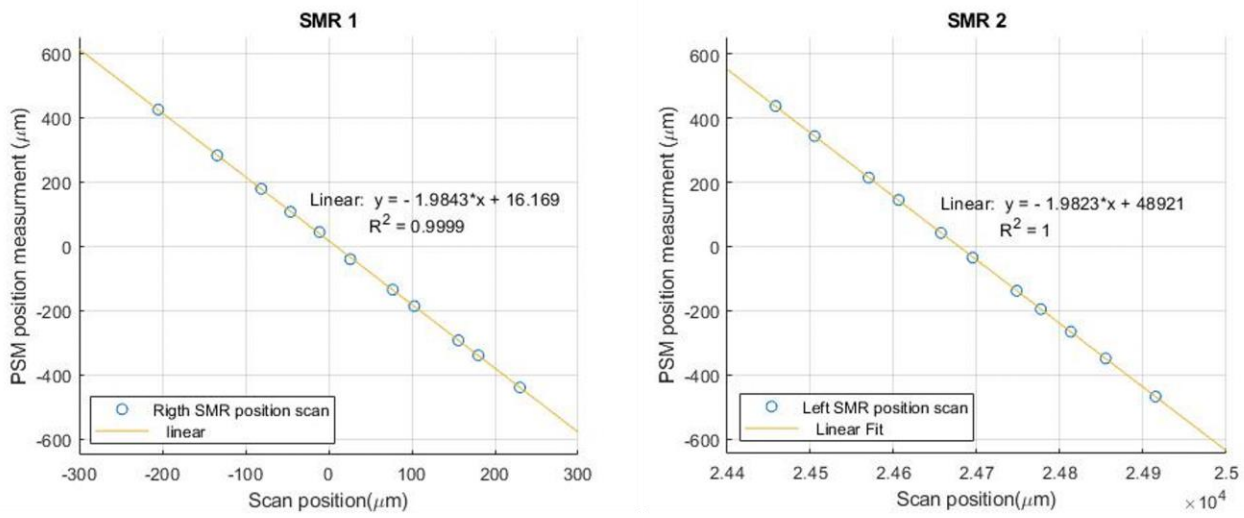


Figure 11 (a) (left) Position scan of SMR 1 at 0° orientation and linear fit. (b) (right) Position scan of SMR 2 0° orientation and linear fit

This procedure was repeated twice more: once for the SMRs rotated about the respective axis perpendicular to their apertures at approximately 90 deg and once for the SMRs rotated about the respective axis perpendicular to their apertures at approximately 180 deg from the initial measurement orientation. The SMRs were rotated to ensure that the scanning method is independent of the scan direction across the SMR. That is the orientation of the SMR does not affect the measurement. The SMR positions are shown in Table 3. The measurements again agree, within a few microns, with the position measurements of the balls. The average measured separation between SMRS was measured to be 24.678 mm.

Table 3 Calculated position of SMR 1, SMR 2, and the relative position between the two SMRs

SMR Orientation	SMR 1 Position (μm)	SMR 2 Position (μm)	Relative Position (μm)
0°	8	24679	24671
90°	-18	24625	24643
180°	26	24693	24719
Average	12	24666	24678

There is a larger error in the SMR measurements when compared to the ball measurements due to the retroreflector vertex decenter. This decenter is a result of manufacturing errors of the retroreflectors. An example of this decenter can be seen in Table 3. It is seen the easiest when one compares the SMR 1 position for the 0^0 rotation and 180^0 rotation. There is a difference of 18 μm in the measured SMR center position. This difference should be approximately twice that of the vertex offset. So, if SMR 1 is rotated 180^0 and SMR 2 is fixed, the measured distance between the SMRs would change by twice the vertex offset of SMR l. It should also be noted that if SMR 1 is rotated by 90^0 and SMR 2 is fixed, the separation between SMRs will be the difference between SMR 1 vertex offset in x and the SMR 1 vertex offset in y.

5. RESULTS AND FUTURE WORK

In conclusion, we successfully demonstrate that one can find the position of rigidly mounted SMRs with a high degree of accuracy. There is very good agreement between the scanning measurement for a ball and an SMR relative position as see

in Table 2 and Table 3. The difference between the SMR separation and the ball separation measurements was only 15 µm. The difference is due to scan errors caused by dust and the joints in the SMR as well as possible misalignments of the retroreflector apexes. There is a larger error in the SMR measurements when compared to the ball measurements due to the retroreflector vertex decenter. This decenter is a result of manufacturing errors of the retroreflectors.

The overall accuracy of the measurement is dependent on an accurate calibration factor for the PSM and the precision of the translation mounts. The calibration for this experiment was conducted by electronically placing crosshairs at the edges of the PSM field of view (FOV) and then finding the crosshair centers. This method relies on a subjective guess as to where the edge of the FOV is located. If one were to use the ball scan method described in Section 2.2, the subjectivity can be removed, and a more accurate and consistent calibration could be achieved.

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