Optical Sensor for use in the R-test

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ABSTRACT
We present a description of an attachment for an autostigmatic microscope that uses two objectives set at right angles to unambiguously locate the center of a ball in all 3 translational degrees of freedom that can be used to perform the "R" test, or to scan a ball plate, to determine machine tool precision dynamically.

INTRODUCTION
Now that five axis machining centers are in wide use, it is advantageous to have a means of verifying their precision over the volume of their workspace that is precise, rapid to perform and is dynamic to show the machine performance in the mode that is used for production. Two methods are commonly used for this performance verification, a ball plate of fixed balls placed at several elevations within the work volume[1] and the "R" test[2] where a multi-axis sensor is attached to the work spindle and a ball is fixed to the work table. Of the two methods the "R" test allows sweeping the work volume fairly rapidly in a continuous motion and yields an assessment of machine performance faster and with more certainty than the ball plate.

Typical sensors for performing the "R" test are a set of 3 or more electronic indicators that engage the surface of the ball mounted on the work table, or a set of 3 capacitance or inductance gauges that surround the ball in a hemispherical fashion. These sensors yield high precision results for the "R" test but cannot be used to scan over a ball plate dynamically because they surround the ball in all 3 axes.

We present an optical sensor that is unobstructed in one axis so that it may be used as an "R" test sensor but may also be used to scan a ball plate, or an array of fine ground cylinders

BALL CENTER FINDER ATTACHMENT
The ball center finder (BCF) is an attachment for an autostigmatic microscope[3,4] (ASM), an optical instrument analogous to an autocollimator but with a finite focus. The BCF replaces the single objective found on ASMs with a beamsplitter to divide the collimated beam exiting the ASM into two beams that are then turned at 90 degrees by fold mirrors and directed into a pair of objectives set at right angles to each other as shown in Fig. 1.

The ASM is the roughly square outline in the upper left of the Fig. 1A and the BCF is the square outline with a cutout in the lower right. Inside the cutout is a ball and the light from the two objectives is focused at the center of the ball. The ball acts like a convex mirror and reflects the light back into the BCF and ASM over paths nearly identical to the paths directed at the ball. The beamsplitter in the ASM directs the light through a tube lens to focus on the detector. If the ball were perfectly aligned to the objectives, and if the BCF were perfectly aligned, the beams of light from the two objectives would focus in precisely the same spot on the detector. Any misalignment of the ball relative to the objectives will produce two spots on the detector, one from each objective, and the relative positions of the spots determine the degree of misalignment of the ball in all three axes.

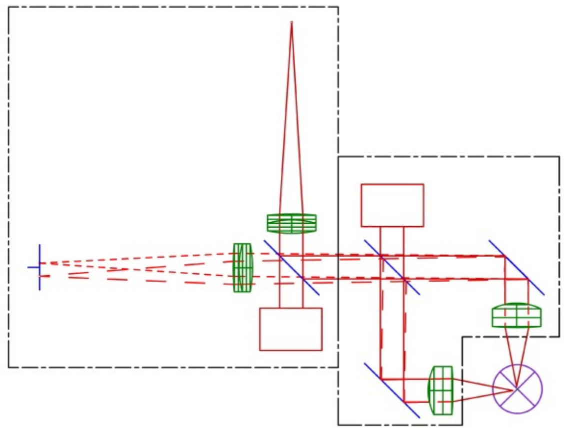

FIGURE 1 Schematic diagram of an ASM with the BCF (right) attached focused at the cneter of a ball.

BEHAVIOR OF THE BCF

In use on a machine tool the most obvious mounting is to have the cutout of the BCF pointed downward from the spindle so the two objectives each point downward at 45 degrees to the Z machine axis, that is, with the BCF in Fig.1 rotated 45 degrees clockwise. In the data to be presented, the unobstructed path of the BCF was oriented along the X machine axis, that is the X axis is into the page in Fig. 1, although it could have just as well be oriented along the Y axis.

As the ball is moved from its centered location in any coordinate direction, the spots on the detector move according to the optical layout of the system, making it possible to unambiguously detect sub-micrometer motions in any direction.

RESULTS

The BCF was attached to the spindle of a 5 axis Mori Seiki NMV5000 as shown in Fig. 2 in order to determine the response of the BCF to motions in each of the 3 machine axes, and to calibrate the pixel motion on the detector of the PSM[5] with the machine motion.

The data in Fig 3 shows the response of the two spots to machine motion in each of the 3 axes individually over the range where the ball is not so decentered as to get non-linear data, and the data show the response was as predicted. There is almost no motion of the spots where there should be none and linear response where there should be. The slopes of the lines give the sensitivity in pixels per micron of machine motion assuming the machine is well calibrated.

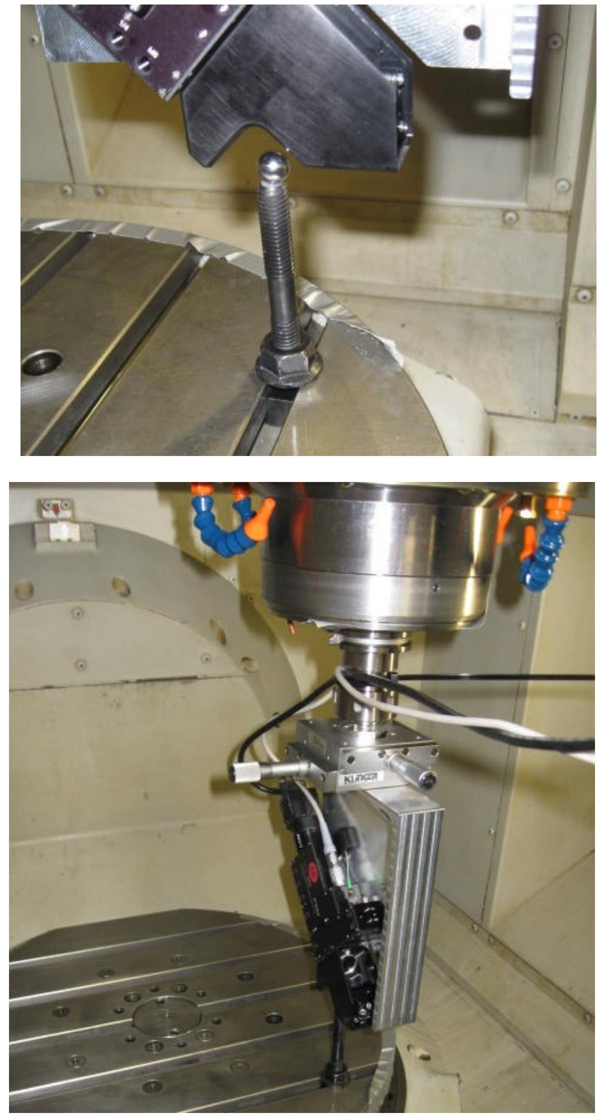

FIGURE 2. BCF centered on ball mounted to work table (above). BCF and PSM mounted on the spindle of a Mori Seiki NMV5000 showing orientation of BCF to machine X axis (lower).

From the slope data in Fig. 3 the sensitivities are 0.543 µm/pixel in x and 0.750 µm/pixel in y and z with the ratio of the sensitivities in x to that in y and z being very close to sin 45° with the assumption that the machine motion was precise. From the nominal design of the BCF the sensitivity in the X axis should have been 0.530 µm/pixel and at an angle 45°, 0.749 µm/pixel.

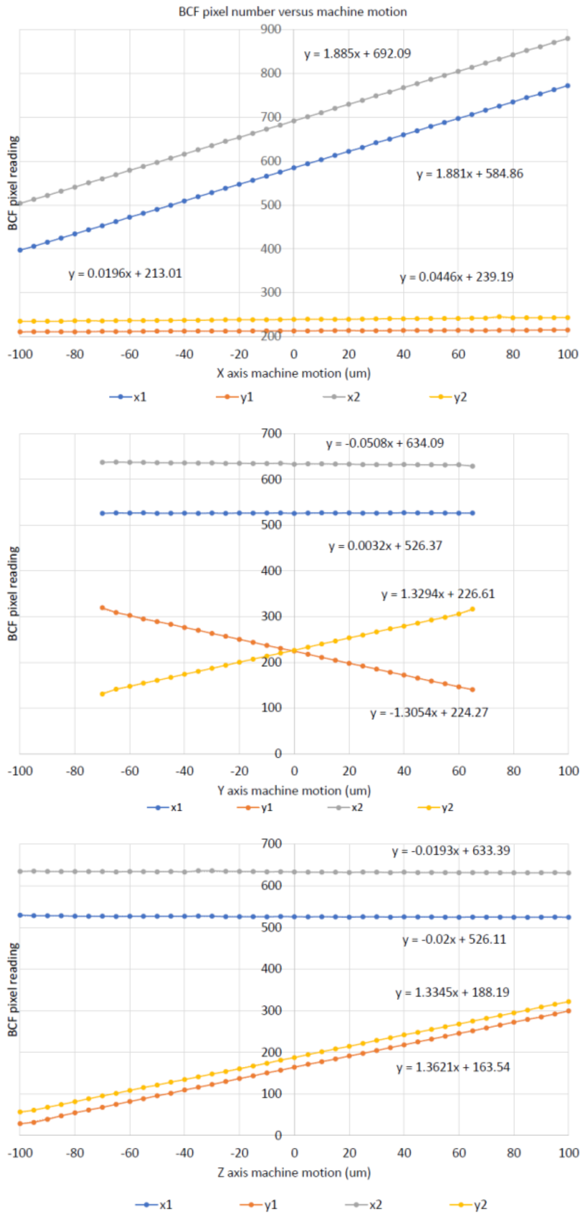

FIGURE 3. Response of the BCF for machine motions in each of the 3 axes, X, Y and Z, top, middle and bottom, respectively. x1 and y1 are the spot location for one spot and x2, y2 the other in units of pixels on the PSM detector. The scale of all 3 graphs are the same in both axes.

From these initial tests it is not known if errors from a linear fit of the data are due to the machine or the BCF without further calibration. However, looking at the detrended data for the 3 motions gives a feeling for the ultimate sensitivity of the BCF. Fig. 4 shows the differences from a linear fit for each of the 3 motions where the x axis or scan direction data are the average of the 2 x spot motions since they only differ in theory by a constant offset.

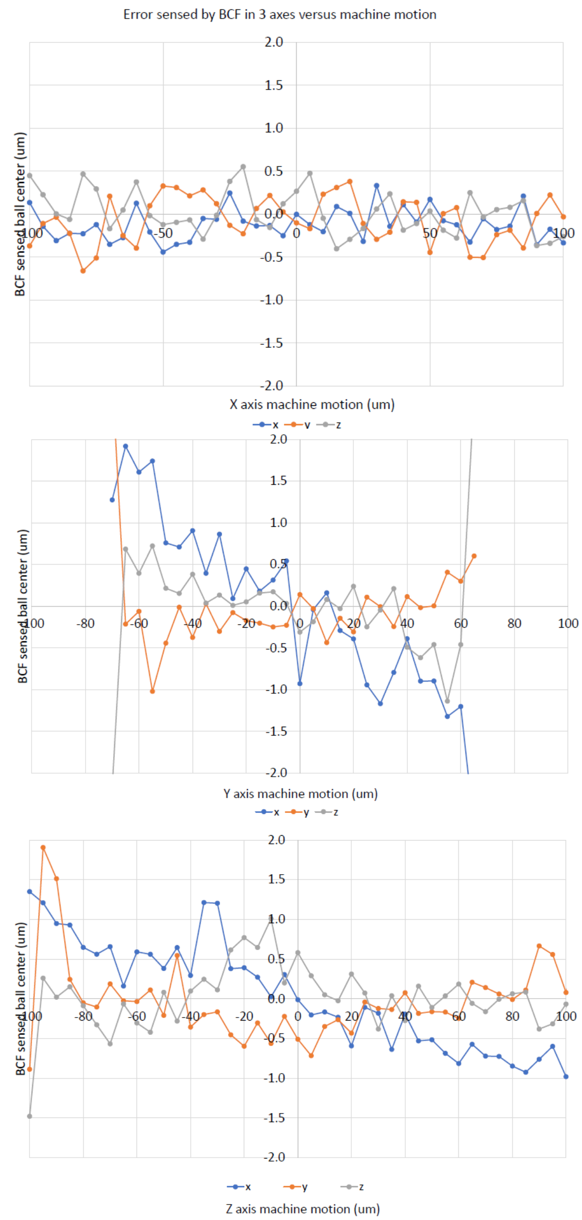

FIGURE 4. Detrended data for the BCF in the 3 axes of machine motion, X to Z, top to bottom. Blue is the BCF X axis response, orange Y and gray Z. All graphs are the same scale in both axes for easy comparison.

These data show that the range over which the BCF is linear is limited to around ±50 µm and that there is probably some small misalignment of the machine axes that accounts for the slope in the X axis data when only the Y and Z are moving.

TABLE ROTATION TEST

Once the sensitivity factor of the BCF was known it was possible to do a test where the C axis of the machine was rotated 360° in 10° increments while the spindle followed. The ball was mounted toward the edge of the table as seen in Fig. 3 so that it swept out a radius of about 308 mm. The BCG data for this test is shown in Fig. 5.

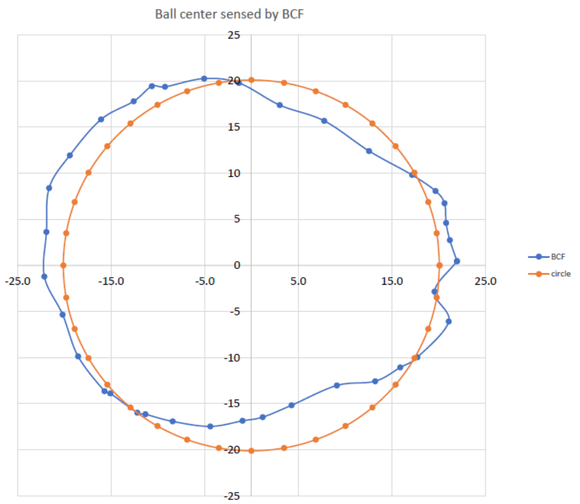

FIGURE 5. BCF sensed errors in the X and Y axes as the C axis was rotated 360° in 10° increments. The units are µm so the worst difference between a perfect circle (orange) and the BCF readings (blue) was about 5 µm.

There is no reason this test could not have been done dynamically as the machine moved but caution was used on these initial experiments. Further, the discrete data points show the apparent random behavior of the small following error of the C axis motion by the spindle. It is assumed that most of the behavior observed is machine following error based on the performance of the BCF shown in Fig. 4.

Further, the BCF also provided information on the apparent error in the Z motion as the table rotated. This data is shown in Fig. 6 where the peak-to valley excursion is about 12 µm but not in a smooth sine curve as one would expect if the error were due to an axis misalignment.

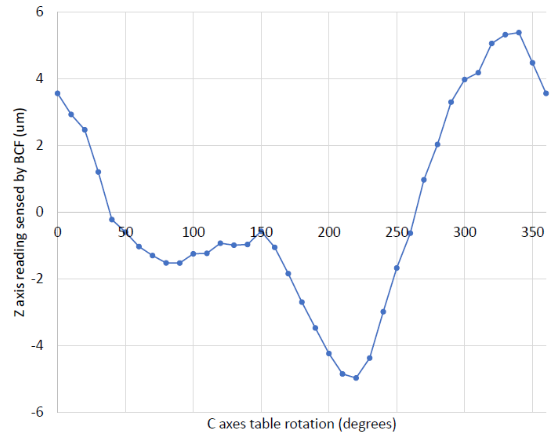

FIGURE 6. Z axis reading sensed by the BCF as the work table rotated 360°

FUTURE WORK AND CONCLUSIONS

It has been shown that the BCF performs essentially as it was designed to do, to be an optical R-test sensor capable of tracking a ball and having the capability to scan along a row of balls in one direction. It remains to do further testing where the full 5 axis motion of the machine is scanned dynamically. Also, tests of repeatability and some sort of absolute calibration such as reversal needs to be done to verify the performance of the BCF alone rather than as a part of the overall machine performance.

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