Computer Generated Holograms as 3-Dimensional Calibration Artifacts

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ABSTRACT

The positioning accuracy of multi-axis machine tools and coordinate measuring machines are often checked using ball bars or ball plates where the spatial locations of the balls are externally calibrated to provide a traceable artifact[1,2]. In use, the individual ball surfaces are probed in at least 4 places with a tactile sensor and the points of contact fit to the equation of a sphere to determine the center of the ball. The method is tedious, indirect and semi-static. Furthermore, it is difficult or impossible to create artifacts that truly span the three-dimensional work volume of machines because some features become occluded by others and cannot be accessed.

CGHs AS CALIBRATION ARTIFACTS

This paper explores the use of computer generated holograms (CGH) as virtual 3D calibration artifacts for multi-axis machine tools. A CGH can be fabricated on a fused silica photomask substrate using a microlithographic process to create very high accuracy artifacts that emulate a wide variety of 3-D shapes, including arrays of balls, cylinders, cones, etc. The virtual features on the CGH are interrogated with a point source of light such as produced by an autostigmatic microscope (ASM)[3,4]. The location of the ball centers in two directions parallel to the plane of the CGH can be read by the ASM with resolution of less than one micrometer, and to a few μm in the third dimension.

Two CGH artifacts are demonstrated here. Figure 1a shows a CGH that has a hexagonal close-packed array of Fresnel zone patterns on 28 mm centers in the CGH plane. Within each pattern are concentric Fresnel zones simulating different ball centers, or heights above the CGH, at heights of 5, 15, 45 and 135 mm. The small zones between the larger array have virtual radii of 6.35 and 12.7 mm to match the radii of common ball sizes. Figure 1b shows an axicon[5] that simulates a cone whose central axis is perpendicular to the plane of the CGH.

In use, the CGH is probed at each plane of virtual balls, or along each virtual line, providing

FIGURE 1: a) virtual 3-D ball array CGH; b) virtual axicon CGH

a check of the positioning accuracy of the machine in three dimensions. In principle, scale errors in all three directions can be measured, along with straightness and squareness of the axes. By comparing positioning errors along parallel lines in the workspace, roll, pitch and yaw error motions of each axis can also be determined.

In this research, a Point Source Microscope is used as the ASM and a Mori Seiki NMV5000 CNC 5-axis milling machine as the test bed. Figure 2 shows the PSM mounted on the spindle of the machine, and the virtual ball array CGH mounted on the table. Note that the PSM allows the ball center positions to be determined in three dimensions with a single measurement, and with sub-micron accuracy in X and Y, and a few microns in Z.

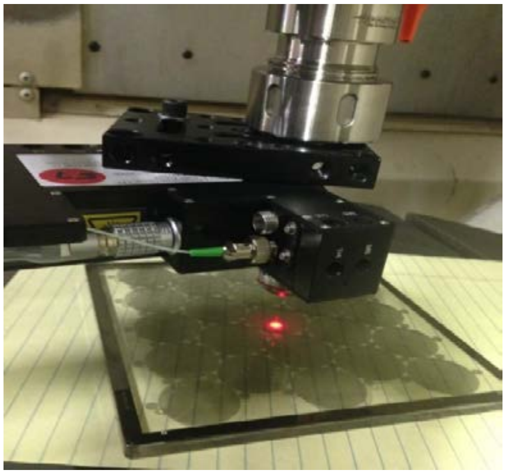

FIGURE 2. CGH on table and PSM mounted in the spindle of the Mori Seiki NMV5000.

PSM SCALE FACTOR DETERMINATION

The PSM “measures” in the X-Y plane by determining the location of the centroid of the reflected spot on a CCD pixel array. Pixel locations are converted into metered coordinates by moving the PSM over known displacements while recording the pixel location of the centroid. Figure 3 shows typical calibration data, resulting in scale factors in the X direction of 1.287 µm/pixel and in the Y direction of 1.285 µm/pixel. The PSM can also estimate position in the Z-direction by evaluating the focus quality of the reflected spot with uncertainties estimated to be in the range of a few microns. Because of the higher uncertainties, the Z measurements of the PSM were not used in this research.

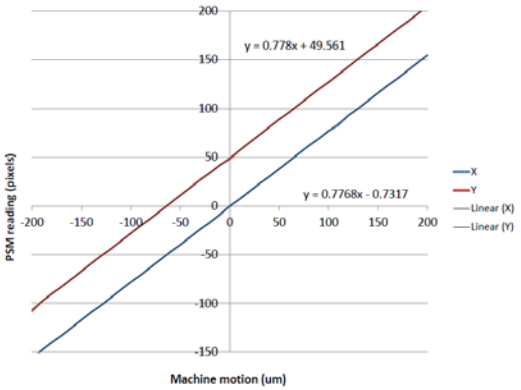

FIGURE 3: PSM Scale factor data in X and Y directions. Curves offset vertically for clarity.

PSM MEASUREMENT REPEATABILITY

The repeatability of the PSM was evaluated by mounting it on a Moore UMM located in a well-controlled environment. This machine is highly stable with vibrational disturbances and axis positioning repeatability on the nanometer level.

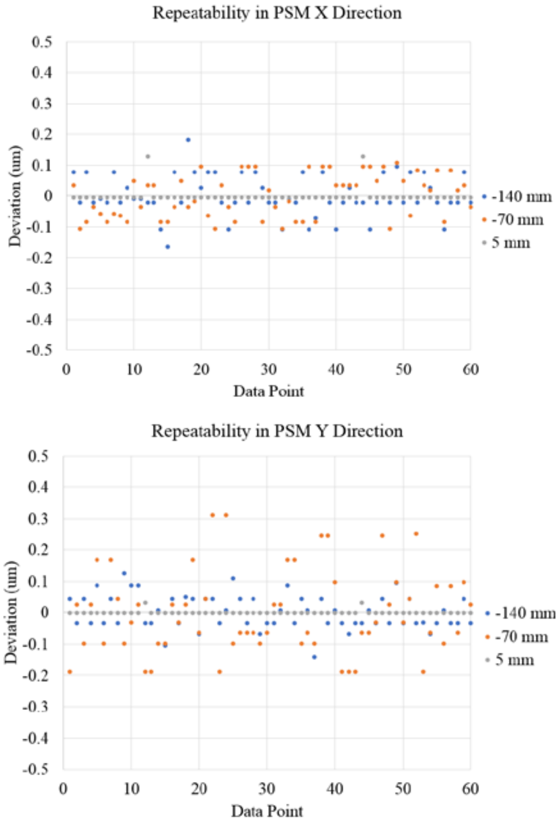

FIGURE 4. PSM measurement repeatability in the X and Y directions.

The PSM was focused on the axicon CGH at distances of 5, 70 and 140 mm from the surface, and readings were taken at 10 second intervals over a period of 10 minutes. Figure 4 shows the results of these measurements in the X and Y directions.

It can be seen that the PSM measurements are repeatable to within a few tenths of a micron. Measurements were also taken by jogging the machine away from the initial position and back multiple times. The results are virtually identical to Figure 4, and consistent with the nanometer-level positioning repeatability of the Moore UMM. The better repeatability at 5mm is largely due to the very short optical path in air.

MORI SEIKI Z-AXIS STRAIGHTNESS MEASUREMENT USING THE AXICON CGH

The axicon CGH was mounted on the table of the Mori Seiki milling machine, and the axes moved to center the PSM over the virtual vertical axis of the CGH. The Z-axis of the machine was then exercised bi-directionally over 300 mm of vertical motion in 5 mm increments. The C-axis of the machine was then rotated 180 degrees and the process repeated; enabling a reversal calculation to separate the straightness errors of the machine Z-axis from the straightness errors of the CGH virtual axis. The best-fit straight line, representing the misalignment between the CGH and machine axes, was removed from each data set. Figures 5 and 6 show the results of these measurements.

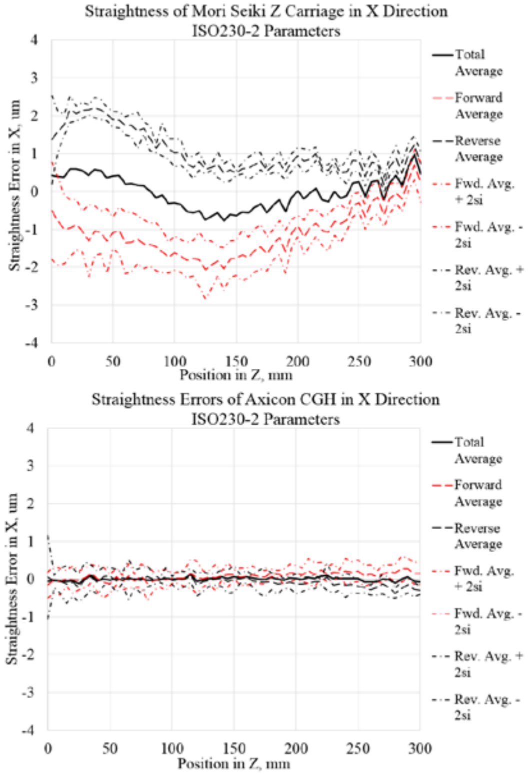

FIGURE 5. a.) Straightness of the Mori Seiki Z axis in the X direction,
b.) Straightness of the axicon CGH virtual axis in the X direction.

The results show that the straightness of the axicon CGH virtual axis is on the same order of magnitude as the measurement repeatability of the PSM, reflecting the expected accuracy of the semiconductor lithographic processes used to create it.

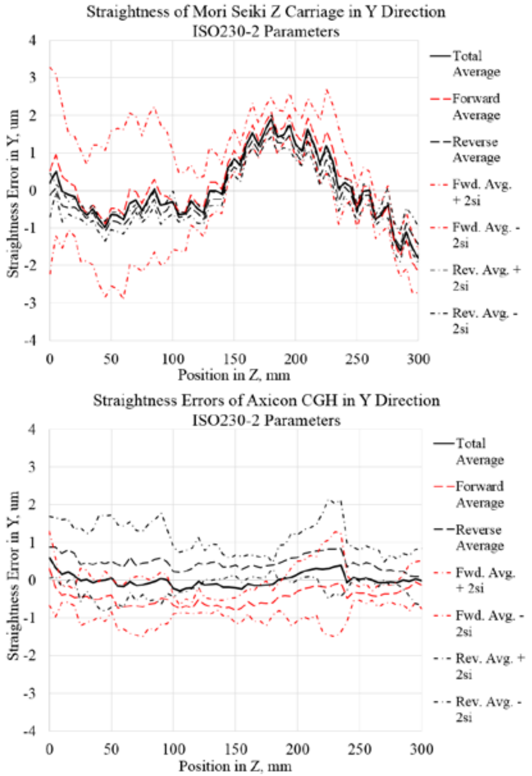

FIGURE 6. a.) Straightness of the Mori Seiki Z axis in the Y direction,
b.) Straightness of the axicon CGH virtual axis in the Y direction.

MORI SEIKI VOLUMETRIC POSITIONING ACCURACY USING THE VIRTUAL 3-D BALL ARRAY CGH

The virtual 3-D ball array CGH was mounted on the Mori Seiki table, as shown in Figure 2. The CGH was aligned with the machine by jogging the machine until the center virtual ball at the lowest level was centered on the PSM display, and rotating the machine C axis until the furthest virtual ball along the X direction had no errors in the Y direction. The machine was then programmed to move to the location of every virtual ball center, and then record the location of the center point relative to the PSM. Each point was approached by moves in the positive X and Y directions, so no axis reversal errors are included in the data. It is assumed in this data that the CGH and PSM measurement tool were perfect and all errors are in the machine. Figure 7 shows the results.

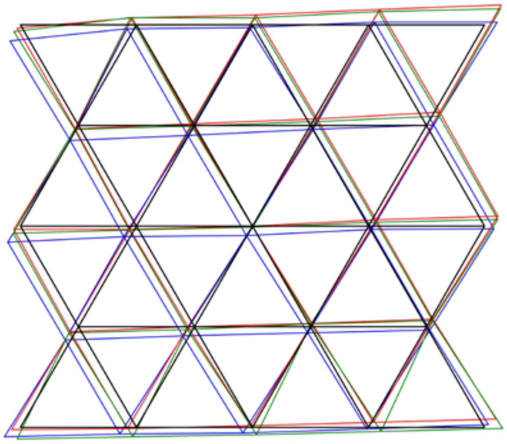

FIGURE 7. Mori Seiki positioning errors using virtual ball array CGH. Black is nominal point location, red at 5 mm above CGH, green at 15 mm and blue at 45 mm. (Note: Errors magnified 4000X for visibility)

Several features are immediately obvious in Fig. 7; there is an overall counterclockwise skewness at all 3 heights. At the lower 2 heights the maps are fairly well aligned, but as the spindle was raised another 30 mm the 45 mm height pattern shifts as a whole toward the minus x and y directions.

In addition, since there are data at 3 heights it is possible to connect corresponding points vertically to determine pitch and roll, while the rotation at the apexes of the triangles gives local yaw. It is apparent there is more data in this map than first appears.

CONCLUSIONS AND FUTURE WORK

Clearly these experiments have barely begun to make use of the potential data here. Also, the CGH used in the experiments was designed to see if it would behave as expected, rather than as an artifact for machine tool calibration. A next version of the CGH would have virtual points evenly spaced in the vertical direction and at larger distances from the CGH to better fill the work volume of a machine tool.

There is also the question of reversal and how to separate errors in the metrology from errors in the machine with the virtual ball artifact. One possibility for reversal is to flip the CGH upside down and view the virtual points through the back of the CGH.

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