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UNCERTAINTY ANALYSIS FOR A SILICON BULK MICROMACHINED DIMENSIONAL METROLOGY ARTIFACT

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ABSTRACT

A mesoscale dimensional artifact based on silicon bulk micromachining fabrication has been developed with the intention of evaluating the artifact both on a high precision Coordinate Measuring Machine (CMM), and on a video-probe based measuring system. A high accuracy touch-probe based CMM can achieve accuracies that are as good as the 2-D repeatability of video-probe systems. While video-probe based systems are commonly used to inspect mesoscale mechanical components, a video-probe system's certified accuracy is generally much worse than its repeatability. By using a hybrid artifact where the same features can be extracted by both a touch-probe and a video-probe, the accuracy of video-probe systems can be improved.

In order to use the micromachined device as a calibration artifact, it is important to understand the uncertainty present in the touch-probe measurements. An uncertainty analysis is presented to show the potential accuracy of the measurement of these artifacts on a high precision CMM.

ARTIFACT DESIGN

The design for the micromachined calibration device takes inspiration from the macroscale, where the step bar is an accepted calibration artifact. Step bars contain measurement planes at well-defined intervals, and are used to determine scale errors along an axis. In order to create an artifact with a measurable step interval on the mesoscale level, bulk silicon etching is used.

Anisotropic bulk micromachining creates structures with crystallographic angles which are based on fundamental physical phenomena, and thus have intrinsic angle accuracy. The edges created between etch planes are sharp to the nanometer level. The micromachined artifact is made of bulk <100> silicon anisotropically etched in a KOH solution, which creates side walls at an angle of 54.74 degrees to the near-vertical <100> plane.

For the mesoscale calibration artifact, 1.5 mm thick, 100 mm diameter silicon is used. Various sizes of trenches, which simulate a step bar, and pitches are designed to have different aspect ratios including some where the etch pits are terminated by the <111> etch planes instead of having a flat bottom. Additional shapes are created on the artifact to serve as tools for the exploration of additional calibration structures. The manufactured calibration artifact is shown in FIGURE 1 [1].

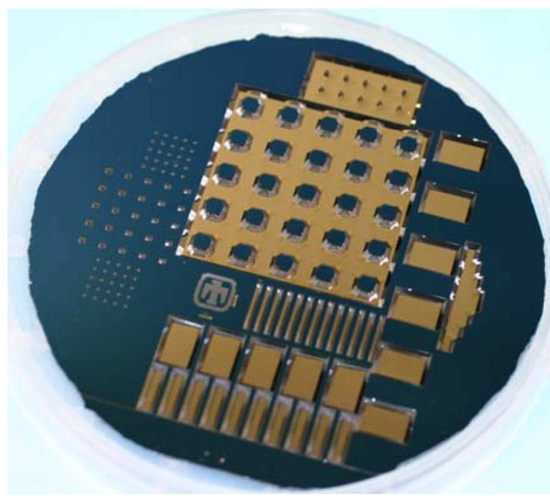

FIGURE 1: Calibration Artifact

The geometric features of the calibration artifact have are sharp edges, which can be determined via an optical probing system or reconstructed by measuring points with a CMM. The sharp edges that exist between the top and etch planes can be seen in FIGURE 2, a close-up view of a mesa structure.

A Moore M48 CMM will be used to probe both the etched planes and the horizontal planes. The computed intersection of the planes is a line segment, which can be imaged with a vision-based inspection system using coaxial lighting.

The spacing between the edges is analogous to the spacing between planes in a step bar.

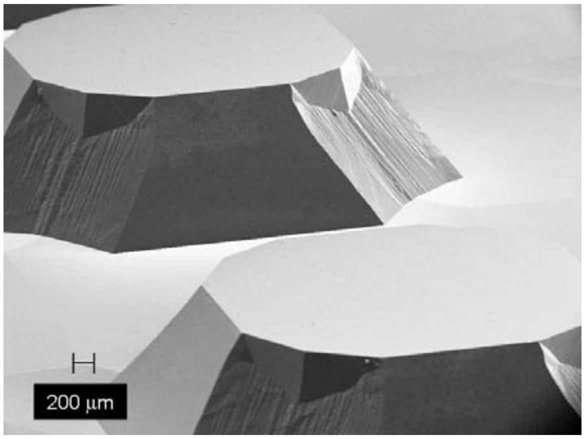

FIGURE 2: Close-up image of a mesa structure.

UNCERTAINTY ANALYSIS METHODOLOGY

In order to use the micromachined device as a calibration artifact, it is important to understand the uncertainty present in the touch-probe measurements. One of the most critical features is the line created by the intersection of the etch plane and the top plane. The touch-probe does not measure this line directly, but instead calculates it based on the intersection between two best-fit planes. It is necessary to understand the uncertainty in the calculated line because the position of the intersection line calculated from data collected on the CMM will be compared to the line directly measured by the video-probe system.

The standard method for uncertainty evaluation is described in the U.S. Guide to the Expression of Uncertainty in Measurement (GUM) [2]. Unfortunately, due to the complexity of the intersection line calculation, using the GUM methodology to determine the associated uncertainty is exceedingly complicated because sensitivity coefficients can not be derived analytically [3].

An alternative to this calculation is to use a Monte Carlo simulation to estimate the uncertainty. Monte Carlo simulations estimate the uncertainty in a measurement by assessing the uncertainty present in a large number of trials whose input conditions are varied according to the expected magnitude and distribution of uncertainty sources.

Monte Carlo simulation has been used by Schwenke et al. [3], Cox et al. [4], Trapet et al. [5], Balsamo et al. [6] and others to assess measurement uncertainty. Future revisions of GUM will include supplemental guides that deal with the use of Monte Carlo simulation as a tool for evaluation measurement uncertainty through the propagation of distributions [4].

In order to determine the uncertainty using a Monte Carlo simulation, it is necessary to first understand the individual sources of uncertainty which contribute to the overall uncertainty of the measurement, and their respective probability distribution functions (PDF).

Once these sources are identified, a model is built to mimic the process which calculates the quantity of interest. In this case the model is dictated by the methods used to calculate each of the best-fit planes and the line formed by their intersection.

Sources of Uncertainty

For this work, the uncertainty lies in the measurement points. Measurement point uncertainty comes from two sources – the touch-probe and the imperfect surface of the part.

Touch-probe uncertainties used for this investigation are modeled based on the repeatability values for each axis of the CMM over a span of time. Based on repeatability tests, the one-sigma repeatability values for the Moore M48 were found to be 15 nm for the two horizontal axes, and 25 nm for the vertical axis. A Gaussian distribution is used to model these uncertainties.

Uncertainty due to surface imperfections is a result of the combination of surface roughness and surface planarity. These numbers are taken from previous experimental work and wafer manufacturer specification, respectively. Surface roughness is 50 nm peak-to-valley. Surface planarity is stated as 1 µin over 1 in, which translates to 25 nm over 25 mm. The uncertainty values due to surface imperfections are modeled as uniform distributions.

Mathematical Model

Given data points lying on two distinct planes, the goal is to calculate the intersection line of the two best-fit planes. To do this, a plane is first fit to each of the sets of data points. Shakarji [7] specified a highly accurate least-squares reference algorithm that is commonly used to fit

CMM data to a plane. The algorithm uses Lagrange multipliers on a constrained minimization problem. Resulting from this algorithm is a point that lies on the plane and a normal vector for each of the fit planes. The line of intersection is then calculated directly from these quantities using widely available analytic equations.

Monte Carlo Simulation

With an understanding of magnitude and sources of point uncertainty and a mathematical model, a Monte Carlo simulation can be run. An example of the data from a single test case is given in FIGURE 3. Each test case starts with the intended measurement points and adds a randomized variation based to the point uncertainty model to create simulated measured data points. The simulated data points are evaluated to determine an intersection line using the algorithm described above. A large number of test cases are run and the set of all intersection lines from the test cases is evaluated to estimate the uncertainty of the intersection line under the given conditions.

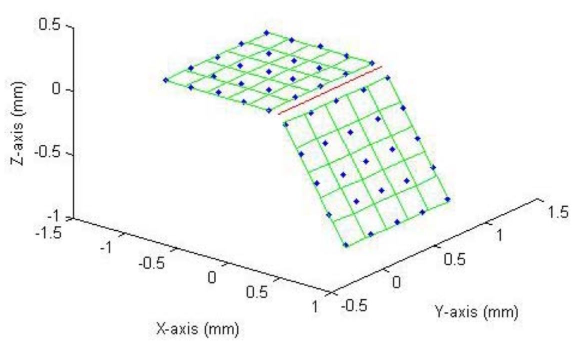

FIGURE 3. Example of Intersection Line for Two Planes

RESULTS

The results presented in FIGURE 4 are from a Monte Carlo trial based on the expected touch-probe measurement locations and associated point uncertainties. In the case of FIGURE 4, a total of 1000 data sets were generated with an intersection line calculated for each trial. FIGURE 4 shows X-Z cross sections of the set of lines at the ends and center of the measurement area. The uncertainty region appears elliptical and varies in size by position along the intersection, with the smallest variation in the center of the measurement area.

In order to quantify the uncertainty, the standard deviations (σ) along the major and minor axes of the elliptical region are calculated. An improved algorithm is used to determine the major axis, as standard routines assume no uncertainty in the abscissa.

The 2σ values at different points along the fit line for a Monte Carlo simulation with 25,000 data sets are given in FIGURE 4. As expected based on the pattern seen FIGURE 5, the deviations are higher at the ends of the line than in the middle. The k=2 uncertainty (95% confidence, or 2σ value assuming Gaussian distributions), along the major axis is approximately 40 nm at the ends, and 32 nm in the center of the measurement area. The uncertainty along the minor axis is approximately 20 nm at the ends, and 16 nm in the center.

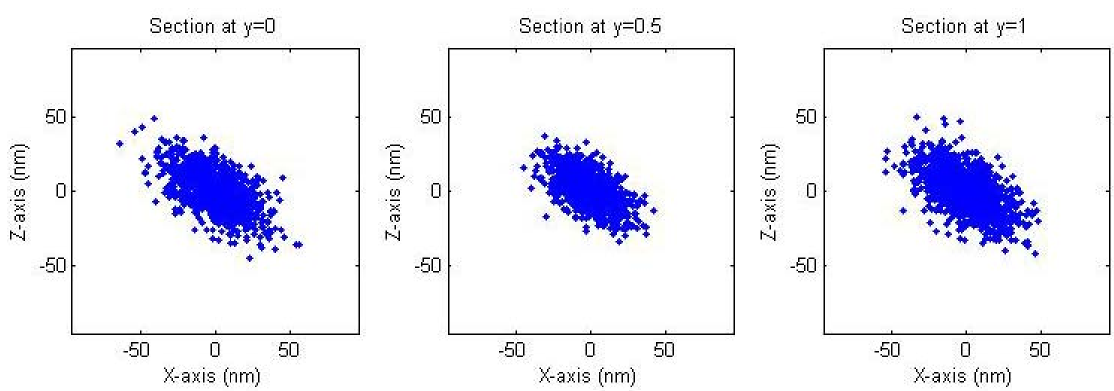

FIGURE 4: Sections at Ends and Center of Intersection Line.

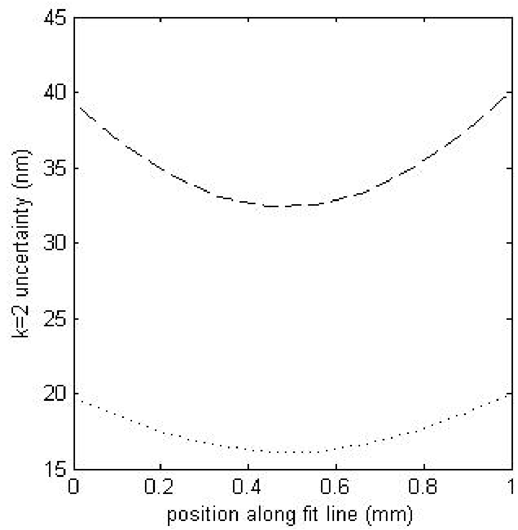

FIGURE 5: 2σ Uncertainty along Intersection Line Based on 25,000 Test Runs

Additional tests were run that varied the number of trials. A variation of a few nm was found in repeated tests with 25,000 trials. This number decreased to less than 1 nm with 250,000 trials. In addition to the number of trials, several other quantities were investigated. It was found that the number of collected data points varies quadratically with measurement uncertainty. To reduce the uncertainty by a factor of two, approximately four times the number of points is required.

Additionally, it was found that, although the area over which the points are collected does not have an effect on uncertainty, the uncertainty varies linearly with the offset of the closest measurement points from the edge. Smaller offsets produce smaller uncertainties.

SUMMARY

The goal of this project is to increase the accuracy of an optical measurement system by increasing the accuracy of the calibration artifact. Current optical calibration artifacts have uncertainty levels around 1 μm. The hope to create an artifact that can be measured with a CMM that has uncertainty levels at 1/10 of the current value, or approximately 100 nm. The numbers calculated by simulation, > 50 nm, are more than 20 times better than the accuracy of current calibration artifacts.

The uncertainty values used in these simulations were taken from literature and from previous experimental work on other artifacts. It is necessary to check the numbers, both for the artifact uncertainty and the CMM uncertainty, to make sure that they agree with the fabricated artifact under current measurement conditions. Even with slight changes in the expected uncertainty values, the overall (k=2) uncertainty of the line fit should remain below 100 nm.

ACKNOWLEDGEMENTS

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