Micro-feature dimensional and form measurements with the NIST fiber probe on a CMM

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Abstract: The NIST fiber probe is a Coordinate Measuring Machine (CMM) probing system intended for diameter and form measurement of micro features and small holes. This Moore M48 CMM at NIST can measure holes down to 500 μm diameter with the Movamatic probe; the NIST fiber probe extends the range to less than 100 μm diameter. Over the last several years, we have performed numerous precision dimensional and form measurements using this probe mounted on the M48 CMM. We have measured size (diameter and thickness) and form (circularity, sphericity, straightness, flatness, conicity) on artifacts such as fiber optic ferrules, fuel injector nozzle holes, knife-edge and cylindrical apertures, ruby spheres, gage blocks, micro gears, and other micro-features on meso-scale components. We briefly describe the probing system and then present a few of the different applications we have studied, highlighting the challenges they represent and the measurement advances our probing system has offered. More importantly, these applications serve to highlight a new calibration service – the dimensional measurement of micro-features at ultra-low forces - that NIST can now offer industry.

1. Introduction.

Micro-parts and micro-features are becoming increasingly important to our economy, but systems for their measurement are still in their infancy. There is tremendous potential for new applications of tiny devices such as MEMS devices (Micro Electro Mechanical Systems) and their progeny (including Micro-opto-electromechanical systems [MOEMS] and microfluidic systems such as lab-on-a-chip [LOC]). Beyond micro-parts per se, macroscopic devices may include microfeatures that are critical to performance. A good example is fuel injectors, where spray holes with less than 100 μm diameter show promise of increasing fuel efficiency and reducing pollution.

The increasing prevalence of micro-parts has stimulated the development of micro measurement systems. These include vision systems for 2-dimensional measurements and 3-dimensional systems such as X-ray tomography or Coordinate Measuring Machines (CMMs) with microprobes. Numerous instrument manufactures, academic researchers and national laboratories have invested in this problem by developing probing systems and micro-CMMs [1, 2]. Of the microprobes, there are a number of varieties, ranging from scaled-down versions of classical macroscopic CMM probes to scaled-up versions of probes originally developed for scanning probe microscopy. A good review of many probing technologies is given in [1, 2]. Here at NIST we have developed a “fiber probe” capable of measuring holes under 100 μm in diameter. There are several varieties of probes that might be described as fiber probes. All of these probes are notable for their ability to measure very high aspect ratio features. The NIST probe, for example, has been used to measure inside small holes at an aspect ratio of 80:1 without noticeable compromise in performance. Among fiber probes, there are at least two varieties that employ a vibrating stylus [3, 4], and at least two varieties where the stylus is static [5-7]. The basic operating principle of a vibrating probe is to detect changes in the amplitude, phase, or frequency of vibration as the probe comes into contact with a surface. A static probe operates in more the manner of a traditional CMM probe, detecting the deflection of the probe tip when it contacts the surface, as described in the next section.

2. The NIST fiber probe

Dimensional metrology of micro-scale features in micro- and meso-scale components is a challenging problem not only because of the small sizes involved, but also due to the requirement of low probing forces. At NIST, we have developed a low-force, fiber-based contact probing system [8] that can be mounted on our high accuracy CMM, the Moore M48[1] CMM. This probe enables the measurement of 100 μm scale features such as a micro-hole to a depth of at least 5 mm (sometimes up to about 10 mm) with extremely small contact forces of the order of 5 μN or smaller. The uncertainty in a diameter measurement for a high quality artifact is generally less than 100 nm ($k = 2$).

The probe stylus is made from a glass fiber with a ball formed on the end. The probe functions by optically imaging the fiber stem from two orthogonal directions a few millimeters away from the ball end of the fiber (Fig. 1). To be more precise, the optical system does not literally image the fiber, but images a narrow line of light brought to a focus by the stem of the probe, creating a very sharp, high-contrast image for which nanometer-level motions are detectable. Upon contacting a part, the fiber bends by a small amount. The magnitude of the deflection at the tip (which is the part over-travel) is related to the observed displacement of the stem at the point of observation by a previously determined calibration factor. The technique and early results are discussed in [8].

It is of interest to compare our probe to the static fiber probe developed at Physikalisch-Technische Bundesanstalt (PTB) (now available commercially [7]). The PTB probe stylus consists of a small ball on the end of an optical fiber. The ball is illuminated through the fiber and a vision system viewing the ball detects when it is deflected by contact with the wall. The NIST system also employs a camera but does not view the ball directly—rather, it senses a deflection of the stylus stem at a point well away from the ball at the end of a long fiber. This approach has both potential advantages and

[1]Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

disadvantages, and it is not clear which approach is preferable. A clear disadvantage of the NIST system is that it must infer position of the stylus tip based on indirect evidence obtained from the stem, and it must be determined if this indirect information is indeed reliable. An advantage of the indirect approach is that detection of the stem above the hole isolates the measurement from disturbing influences that might be present when imaging inside the hole, such as reflections and diffraction. Also, there may be significant advantages in using the unusual optical detection technique described above (fiber is not directly imaged) with its high-contrast image of a fine line of light. In the final analysis, which system is preferable might well depend on the measurement task and on the environment in which the probe is used.

The deflection mode of operation as described above is the general mode in which the NIST fiber probe is employed. A variation of this deflection mode of operation is the vibration assisted pseudo scanning mode where the probing system operates as a 1D roundness instrument. The part is mounted on a precision spindle and the probe is always in contact with the part. To overcome surface adhesion, the fiber is excited into resonance as the part is rotated from one sampling position to another. We have discussed this enhanced capability in [9].

Another mode of operation of the fiber probe is "buckling mode" (also discussed in [9]). This mode of operation is needed when measurements directly along Z are required. When the probe is brought in contact with the part along the Z direction, the fiber buckles on contact and the amount of machine over-travel is determined as in the deflection mode by a prior calibration.

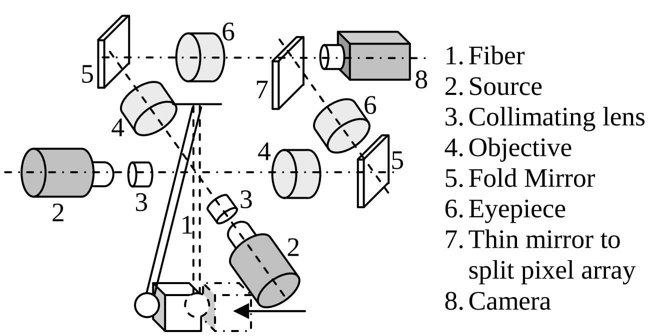

Figure 1 Optical setup for fiber probe when employed in the deflection mode of operation

3. Applications

Over the last several years, we have performed several high precision dimensional and form measurements using our fiber probe mounted on the M48 CMM. We have measured size and form of numerous artifacts. We describe a few interesting applications where either the small part size and/or contact force limitations in combination with high accuracy requirements have necessitated measurements to be made with our fiber probe.

3.1 Internal geometry of a 127 μm diameter, 10.5 mm long hole in a fiber optic ferrule

Measuring large aspect ratio micro-features at low uncertainties is a major challenge in dimensional metrology. The internal geometry of a fiber optic ferrule is a typical example; in fact the ferrule was a primary driver for development of the NIST fiber probe. With a nominal diameter of 125 μm, a measurement to a depth of 5 mm inside the fiber optic ferrule represents an aspect ratio (depth to diameter) of 40:1. We have performed several measurements inside a ferrule at these depths at expanded uncertainties under 100 nm (k = 2). Some early results are shown in [8].

As an interesting test, we recently attempted to increase our working depth to the entire length of the ferrule, which was 10.5 mm long. This represents an aspect ratio of 82:1, which is a significant advance in micro-feature dimensional metrology capability. In order to achieve the increase in working depth with the same fiber probe (its length remains unchanged), we had to move the point of observation on the stem closer to the fixed end of the fiber thus reducing the sensitivity of the fiber. In addition to lower sensitivity, there is also the potential problem of non-linear bending due to external forces such as static charge which could lead to measurement errors.

A simple test of the performance of the probe at extended working depth of 10.5 mm is to measure the hole near its mouth, then invert the hole and measure the same region of the hole by inserting the fiber all the way into the hole. Any disagreement in diameter and form is an indication of potential problems associated with stem-wall interactions or other sources of error that vary with depth inside the hole.

We measured the hole at depths of 3 mm and 4 mm from the mouth, then reversed the hole and re-measured it from the other end at depths of 7.5 mm and 6.5 mm. The diameters obtained at the 3 mm and 4 mm depths were 127.39 μm and 127.37 μm, while the diameter (entering the hole from the opposite end) at the 7.5 mm and 6.5 mm depths were 127.37 μm and 127.35 μm. This excellent agreement indicates that there is little degradation in our measurement capability at large depths.

Fig. 2 (a) shows a photo of the fiber probe entering a ceramic ferrule. Fig. 2 (b) shows the radial deviations at the 3 mm position measured from one end and the corresponding 7.5 mm position measured from the other end. It is clear that the radial deviation plot shows excellent agreement. Similar agreement in radial deviations was observed for the 4 mm and 6.5 mm positions also.

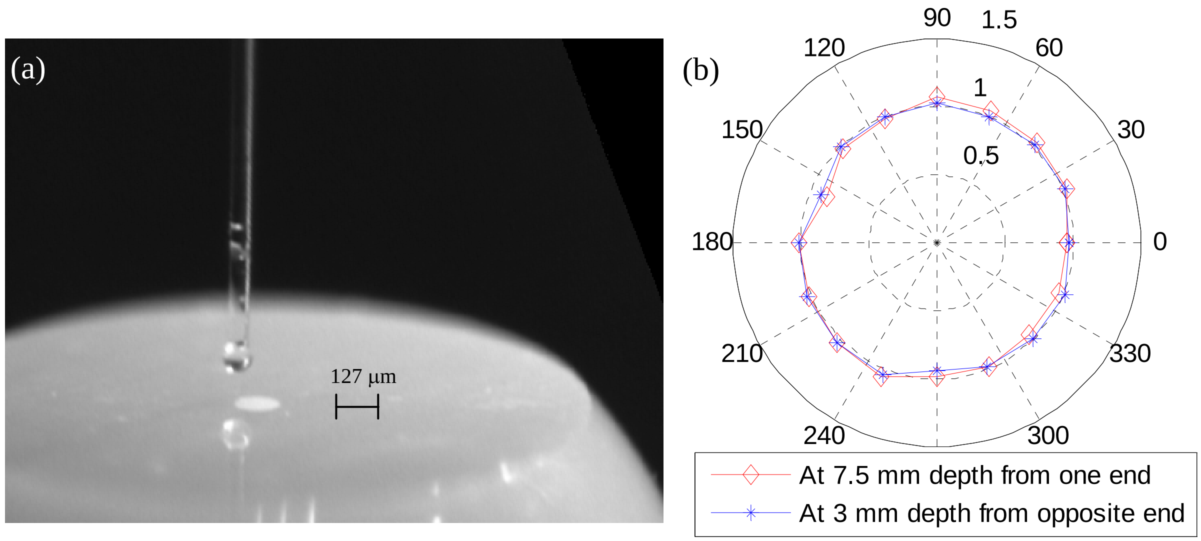

Figure 2 (a) A 127 μm diameter hole in a fiber optic ferrule **(b)** Radial deviation plot at the 3 mm depth inside a ferrule measured from one end of the ferrule and the corresponding 7.5 mm depth measured from the other end of the ferrule.

3.2 Internal geometry of a reverse tapered hole in a fuel injector nozzle

Mapping the geometry of fuel injector nozzle holes is critical in improving fuel efficiency of automobiles and therefore in reducing harmful emissions. Nondestructive technologies such as X-ray computed tomography are sometimes used, but the uncertainty in these methods is large and difficult to assess without an independent measurement technique. Fiber based contact probes offer a unique solution for this challenging measurement problem.

We have measured several micro-holes in a fuel injector nozzle where the diameter of the hole increased with depth (i.e., reverse tapered hole). The nominal diameter at the mouth (fuel exit location) was 130 μm while the diameter at a depth of 0.8 mm (fuel entry location) was 150 μm. In order to measure this taper, we had a special probe fabricated with a ball of larger diameter (100 μm diameter ball) mounted on a thin stem (50 μm diameter stem). This allowed a larger working range so that when the probe is deep inside the hole, there is no contact between the stem and the edge of the hole near the mouth. Fig. 3(a) shows a picture of the fiber probe entering the hole, and Fig. 3(b) shows a 3D form plot of the internal geometry of the hole.

The uncertainty in these diameter measurements was under 200 nm (k = 2). The largest uncertainty contributors were the poor form/surface finish of the hole. Therefore finite sampling and mechanical filtering introduced errors that were significantly larger than other sources such as uncertainty due to probing system, machine positioning, probe ball calibration etc.

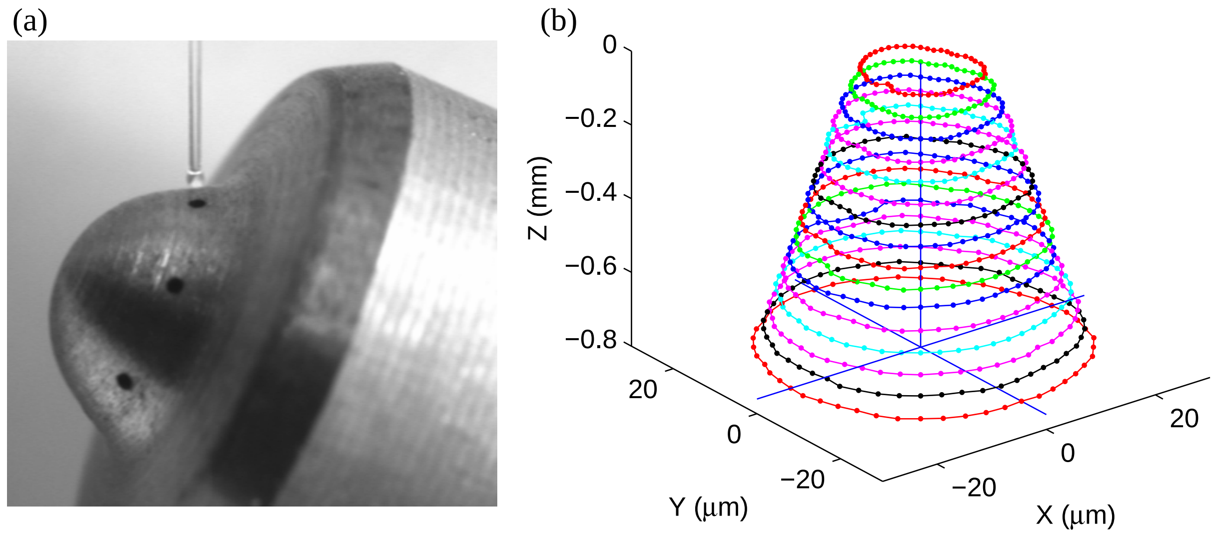

Figure 3 (a) Photo of the fiber probe entering a reverse tapered micro-hole in a fuel injector nozzle, 0.8 mm deep, diameter ranging from 130 µm to 150 µm **(b)** 3D plot of the data from inside the micro-hole (the data has not yet been compensated for probe radius, hence the x and y axes scales are smaller than expected)

3.3 Area of knife-edge apertures used in radiometry/photometry

A significant advantage of fiber based probes is the extraordinarily low contact forces they exert on the part during a measurement. For instance, our fiber probe exerts a force of less than 5 µN during a typical measurement. This is based on cantilever beam calculations where the nominal geometry and deflections are known.

An interesting macro-scale application where such low forces are useful is the determination of the area of knife-edge apertures. Apertures are used as standards in radiometry and photometry where high accuracy area measurement is required. These apertures may have a cylindrical wall, or may have a sharp edge. The diameters range from several millimeters to about a hundred micrometers or smaller. The cylindrical apertures may be measured with a traditional CMM probing system (if the diameter is not too small), but the knife-edge apertures have such delicate edges that they can only be measured optically or using an ultra-low force probing technique. The uncertainty in optical methods may be small but the agreement between different optical methods is sometimes larger than the uncertainty, as an inter-comparison study showed [10]. We should point out that while the contact forces are very low, the contact pressure on a sharp knife edge aperture may potentially be at or near the yield strength of the material. We have attempted to estimate the contact pressure and any deformation due to hertzian stresses in [11].

We therefore attempted to measure these knife-edge apertures [11] with our fiber probe. Our measurements and analysis suggested that the uncertainties in diameter using the fiber probe are extremely small - of the order of 0.06 µm (k = 1) to about 0.17 µm (k = 1) depending on the aperture. The largest uncertainty contributors are the part surface roughness and form; the contribution from the probing system is extremely small in comparison. Further, our measurements and uncertainties are validated on cylindrical apertures which could be measured using well established traditional probing systems on CMMs.

An interesting aspect to these knife-edge aperture measurements was that we used the cylindrical portion of the stem as the probing element instead of the sphere at the end of the stem. This is because a sphere is sensitive to any warp or tilt in the aperture leading to potentially large errors if contact occurs above or below the equatorial plane of the sphere. A cylindrical stem, on the other hand, is fairly uniform in diameter over a short portion; its size and shape can be calibrated using a master sphere. Fig. 4(a) shows a picture of a knife-edge aperture and Fig. 4(b) shows an example profile of a knife-edge aperture measured with our fiber probe.

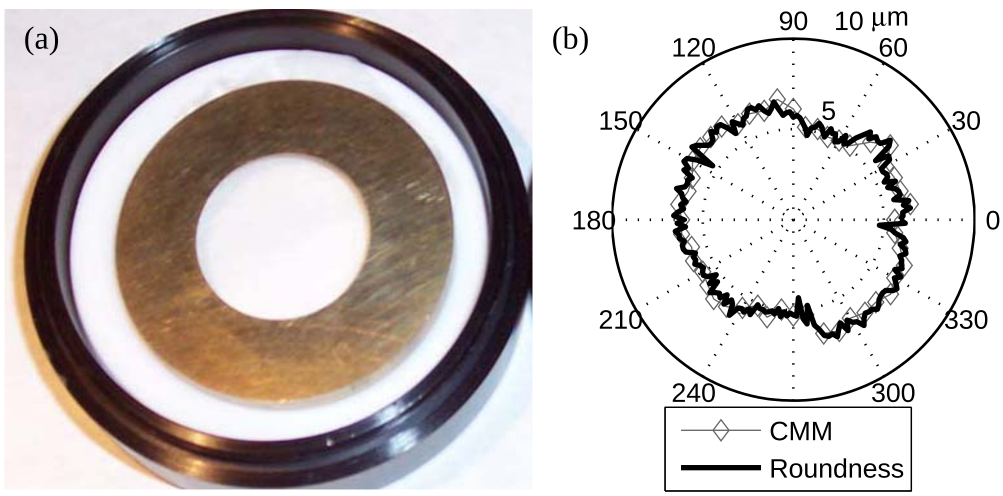

Figure 4 (a) Picture of a knife-edge aperture **(b)** Radial form of an aperture. The aperture was measured with our fiber probe operating in 2 modes: The CMM mode is the typical mode of operation where the part is mounted on the machine table and the probe operates in touch-trigger mode. In the roundness mode, the part is mounted on a spindle and the probing system operates as a 1D roundness instrument.

3.4 3D measurements of micro-scale features such as hemisphere and cone on meso-scale components

Measuring the 3D geometry of micro-scale features is even more challenging than measuring 2D sections on 3D artifacts for several reasons. The probe diameter and form has to be calibrated over the entire region of the probe that contacts the part unlike for a 2D case where only the equatorial plane of the probe ball is of interest. While probe balls on the styli of traditional probing systems have excellent sphericity, probe balls on micro-scale probes are generally of unknown quality. The probe balls that we utilized on our fiber probe were nearly spheroidal in shape, longer along the *Z* axis than along *X* or *Y* by about 2 μm. The residuals from the best-fit spheroid were within a ±0.25 μm band.

A somewhat related issue that makes the measurement of 3D geometry challenging is that of probe radius compensation. If the probe ball can be assumed to be a perfect sphere and surface normals are along probing direction, probe radius compensation is easy to perform. If the probe ball has arbitrary geometry and when the part feature size is comparable to probe size, probe radius compensation involves detecting surface normals at the point of contact. The surface normals themselves are not necessarily along the direction of machine motion because the flexible probe is free to bend and make contact at any point lateral to the direction of motion. Therefore, the analysis of the data becomes a fairly involved mathematical problem by itself.

A recent application we studied involved a component that comprised a 35 μm nominal radius hemisphere located on a cone whose half-angle was nominally 20°. The region of interest was the top 130 μm portion of the part. After calibrating the probe, we measured more than 500 points on the part. Subsequently, we employed a least-squares best-fit method for probe radius compensation where we recognized the fact that the probe was spheroidal in shape and that in addition, it had some small tilt about the *X* and *Y* axes. A photo of the part being measured is shown in Fig. 5(a) and the points on the surface after probe radius compensation are shown in Fig. 5(b). We have not yet developed uncertainty budgets for this application.

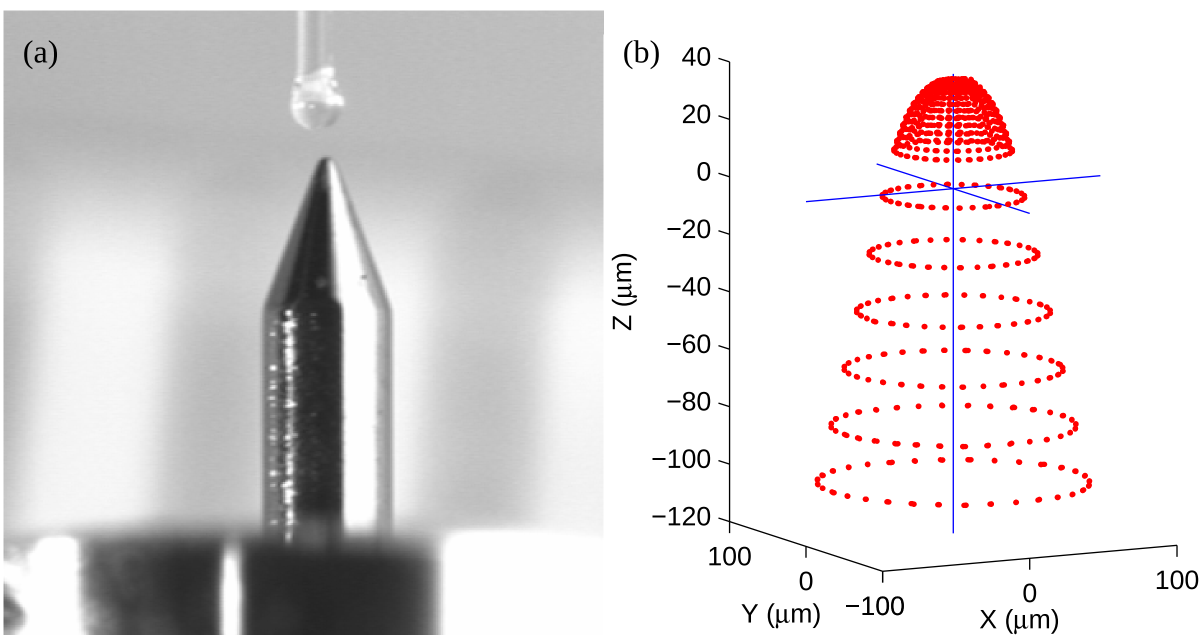

Figure 5 (a) Photo of the probe measuring a hemisphere-cone artifact **(b)** Points on the surface of the hemisphere-cone artifact

3.5 Micro-holes in micro gears

We recently measured micro-holes in several micro-gears produced by a LIGA process. ("LIGA" is a German acronym describing a production process for high-aspect ratio MEMS-like structures.). The gears varied in thickness from 0.15 mm to about 1 mm, while the central holes were about 0.25 mm in diameter. Again, this application required a small probe size and low contact force; our fiber probe was therefore an ideal probing system in this case. Our measurements indicated that the hole was generally tapered and that not surprisingly, dirt may be a large contributor to the uncertainty in the measurement. Fig. 6 (a) shows a picture of the probe entering the micro-gear and Fig. 6 (b) shows a form plot of the data from inside the hole. There are several points deep inside the gear that may possibly be dirt. While we have not quantified an uncertainty in diameter at any depth, our experience in making measurements on similar artifacts suggests that the part surface texture and form, and possibly dirt, will be the largest contributors to the overall uncertainty.

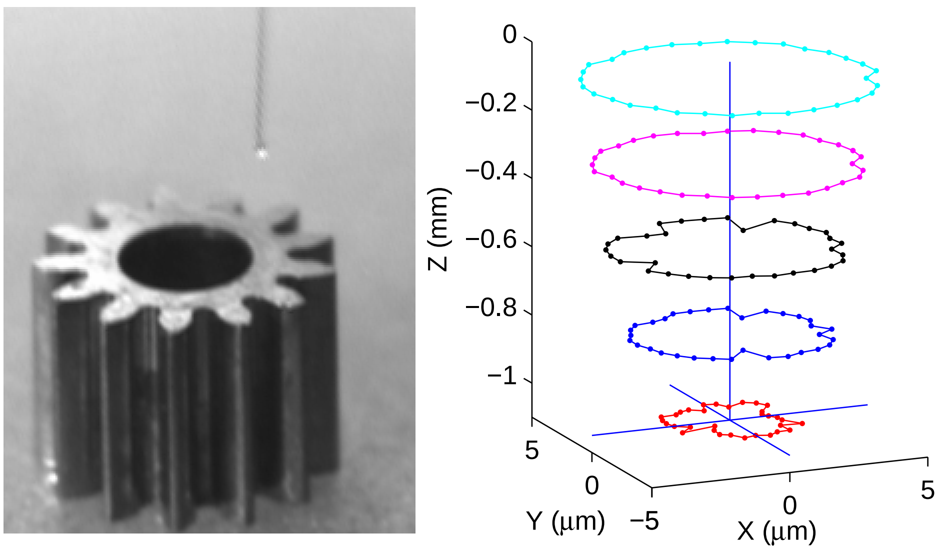

Figure 6 (a) A picture of our fiber probe entering a micro-hole in a micro-gear **(b)** Form plot of the central hole in the gear showing both the taper and possible outliers (dirt) in the data.

4 Error sources

There are numerous error sources associated with a fiber probe measurement. While some error sources are typical in any CMM measurement such as machine positioning accuracy, environmental effects, probe diameter and form calibration errors, etc, there are other sources of error that are unique to the fiber probe. The fiber position is detected by imaging the stem; imaging uncertainty, although extremely small, is therefore a contributor. The non-orthogonality of the two imaging axes and their misalignment with the machine's axes is also critical when measuring small features. We compensate for this error by measuring the magnitude of the misalignment and software-correcting the data.

The flexible fiber stem is susceptible to external forces such as air currents and electrostatics, and the resulting non-linear bending in combination with other error sources such as axis-misalignment may produce errors. We reduce the influence of these effects to some extent by shielding the probing system from air currents and placing Polonium strips near the fiber to dissipate static charge. The fiber itself cannot be coated with metal because the imaging technique we use relies on the glass fiber behaving as a cylindrical lens.

Geometric effects such as probe radius compensation are another unique source of error, particularly when the surface normals are unknown, or when probe imaging axes are misaligned. Mechanical filtering is also a potential error source especially since the probe size is comparable to part feature size. Dirt is a major problem when performing measurements at low forces where contact forces are insufficient to dislocate particles. We have explored these unique error sources in several articles [12-14].

5 Future Directions

Requirements for accurate 3-dimensional measurements of microfeatures are increasing in step with improvements in manufacturing techniques. Production techniques such as LIGA process and other micro-manufacturing methods (micro-milling, grinding etc) already produce parts with low surface roughness that could benefit from the intrinsic accuracy of our method. Further, unique measurement needs arising from cutting edge applications serve as further drivers of our technique, for example, tiny thin walled targets for high energy physics experiments (such as for the National Ignition Facility targets), soft foams (airogels) for space applications etc. To meet this emerging need, we must continually improve NIST capabilities; our fiber probe is a step in that direction. We face several problems. As discussed previously, one significant challenge is simply dirt: cleaning dust or debris from a micro-hole with greater than 40:1 aspect ratio is a problem that would benefit from more study. Furthermore, although our M48 CMM provides an excellent platform for the fiber probe, it will not be able to keep up with rapidly-developing micro CMMs unless additional small-scale metrology is retrofit to the machine. Finally, we expect to interface several new probing systems to our CMM and explore performance of these probes for various types of measurements. Through such steps we hope to keep in step with evolving industry needs.

6 Conclusion

The NIST fiber probe was developed in response to a growing need to provide high accuracy dimensional and form measurements on a variety of micro-scale features in micro- and meso-scale components. Even large components such as turbines have tiny holes that are sometimes required to be characterized with low uncertainties. The fiber probe provides a bridge between two extremes of measurement capabilities we currently have at NIST - sub-micrometer level accuracy measurements on meso-scale parts on the

Moore M48 CMM and sub-nanometer accuracy of micro-scale parts with atomic force microscope (AFM) and other scanning methods. In providing sub-100 nm level uncertainties on micro-scale components, we have attempted to meet a growing industry need in the area of micro-manufacturing.

The fiber probe is currently in a transition phase from research to application. We have over the last few years measured numerous artifacts that were brought to our notice by customers and colleagues. We have highlighted some of those applications in this paper to illustrate the capability of our probe and more importantly, to highlight a new calibration service that NIST can now offer industry.

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