Probe Technologies for Micro/Nano Measurements

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***Abstract*—Conventional probes for dimensional measurement of parts in macro scale are no more capable for the meso- to micro-sized parts that require accuracy to the degree of 100nm to 10nm. This paper will discuss the needs of probe technologies for micro/nano measurements. Both of the non-contact and contact types of probes will be addressed. For the non-contact probe, the principles and applications of focus probe and confocal microscope are introduced. Developed systems show the focus probe can reach to the accuracy of 1nm and the confocal microscope has 0.1µm accuracy. For the contact type, the fabrication of micro probe tip and a newly developed 3D touch probe are described. Experiment shows the minimum contact force can be as small as 50µN.**

***Index Terms*—focus probe, confocal microscope, contact probe, micro parts.**

I. INTRODUCTION

By definition, the nano-scale ranges from 100nm to 0.1nm. Any new development with size or function falls into this range is named "nanotechnology". The approach of nano-scale research can be in two ways: the bottom-up and the top-down. The bottom-up structure is built up with molecular particles and is the focus of science researches. The top-down approach is to miniaturize visible components from macro to micro sizes and finally downscale to nano-size. This is the way that the engineering technology can discover.

The mission of an engineer is to develop some technologies that can benefit to the industries. From the mechanical engineering point of view, the related manufacturing technologies at various scales can be shown in Fig. 1 [1]. Most of the current industrial technologies still remain in the meso- to macro-scale level of the feature size. During the past decade, the MEMS (Micro-Electro-Mechanical System) and energy beam lithography technologies have attracted some professors, researchers, and companies to work in the material processing in the size feature from micro to high nano scales (1oonm to 10nm). In order to follow the fashion, the name of MEMS has been changed to NEMS (Nano-Electro-Mechanical System) in recent years. The NEMS, however, can only provide manufacturing process in two and half dimensions (2.5D) through layer deposition, etching, etc. For the true 3D micro parts fabrication the concept of micro machine tools has to be realized. This is the new focus after the nanotechnology in the world, namely the "micro/nano system" [2, 3]. A typical example can be found from Sasaki [4] who successfully used an ultra-precision 5-axis micro-milling machine to cut a complex sculpture BOSATSU model in 2mm size.

It is understood that the metrology should always follow the step of manufacturing to ensure the quality of the products. For any 3D profile the 3D measurement must be employed. Conventional macro-scale 3D coordinate measuring machine (CMM) is available in the market. The technology of micro/nano-scale 3D CMM is still a bottleneck for the industry.

This paper will discuss the needs of probe technologies for micro/nano measurements in a micro-CMM [5]. Both of the non-contact and contact types of probes will be reviewed. For the non-contact probe, the principles and applications of focus probe and confocal microscope will be particularly addressed. For the contact type, the fabrication of micro probe with quality spherical tip will be introduced. Some newly developed 3D touch probe mechanisms will be described.

II. NON-CONTACT MICRO/NANO PROBES

A. Focus probe

Although there have been some probes on the market that can measure micro parts to the resolution of 1nm or less, such as the SPMs and white light interferometer, they are all stand-alone systems, which are not suitable to mount onto a micro-CMM.

The first type of this probe to be introduced is the laser focus probe, which adopts the astigmation principle [6]: Its measurement principle can be expressed by Fig. 2. A light from a laser diode is primarily polarized by a grating plate. Having passed through a beam splitter and a quarter wave plate (mounted on the beam splitter), it is focused by an objective lens onto the object surface as a spot approximately 1 µm in diameter, about 2 mm from the sensor. The reflected beam signal is imaged onto a four-quadrant photo detector within the sensor by means of the quarter wave plate. The photodiode outputs are combined to give a focus error signal (FES) which is used to respond to the surface variation. At the focal plane the spot is a pure circle. When the object moves up or down away from the focal plane, the spot appears an elliptical shape in

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different orientations. The corresponding focus error signal (FES) provides an S-curve signal proportional to the object movement, as shown in Fig. 3. Previous studies showed that on a single material, such as DVD disk, this probe can accurately measure 3D surface to nanometer accuracy [6, 7]. Products fabricated by NEMS process are, however, mostly built up different materials on the silicon substrate. Like other types of scanning probes, such as the hologram diffraction method [8] or the SPM (Scanning Probe Microscope) methods [9], non-contact probes always have different characteristics curves with respect to different materials. A solution that utilizes the normalized FES (NFES) technique is proposed to cope with this problem.

When the probe measures a sample surface with high reflectivity, the NFES signal is:

$$S_H = [(A+C)-(B+D)]/(A+B+C+D) \quad (1)$$

If the probe measures a sample surface with low reflectivity, the signals of the four quadrant sensors reduce K times at the same time, and the NFES is:

$$\begin{aligned} S_L &= [(A/K+C/K)-(B/K+D/K)]/(A/K+B/K+C/K+D/K) \\ &= [(A+C)-(B+D)]/(A+B+C+D) \end{aligned} \quad (2)$$

As shown in Eq. (2), the S-curve of sample surface with low reflectivity is the same as the one of high reflectivity. It proves that the probe could measure the 3D profile successfully no matter the surface contains any kind of material.

Calibration tests were conducted on different materials with the focus probe mounted onto a nanopositioning machine, made by SIOS Co. model NMM1 [10]. Fig. 4 plots the calibrated FES and NFES curves of different materials. Due to the different reflective ratios each material has independent FES curve. After employing the normalization technique, all the NFES curves are almost the same. Fig. 5 presents an example of the measurement on a NEMS part composed of two different materials. With the use of NFES technique on the focus probe, it can measure any composite surface.

B. *Confocal probe*

In recent years, the technique of confocal microscopy, first described by Minski in 1957 [11], has become a more and more powerful tool for surface characterization, in parallel with the development of computer-based image processing systems. The basic principle of confocal microscopy (Minski named it double focusing microscopy) is shown in Fig. 6. Light emitted from a point light source (for example a laser beam focused onto an illumination pinhole) is imaged onto the object focal plane of a microscope objective MO (the first focusing). A specimen location in focus leads to a maximum flux of light through the detector pinhole (the second focusing), whereas light from defocused object regions is partly suppressed. The variation of the detected intensity is a function of distance change. It, however, can only measure point by point. The white light confocal microscope was then proposed to measure one area profile at a time in conjunction with digital image processing technique. However, in order to detect the whole surface profile one more scanning principle has to be added, such as the point scan by rotating a Nipkow disk [12] or the structure light projection method with DMD [13].

A low cost confocal microscope probe for area detection has been developed in this research. The system principle is shown in Fig. 7. It uses a high intensity LED to project light through an image fiber bundle onto the work surface. The fiber bundle consists of 80000 fibers with about 150μm in diameter each. The hexagonal grid pattern of the fiber bundle projected onto the work surface can be treated as a structural light. In the collected image frame the grey level change of the pixels is proportional to the distance out of focal plane of the probe based on the triangulation principle. Fig. 8 shows an example of the photo spacer profile measurement on the LCD color filter plate. The microscope is focusing on the substrate and its image is confocal to the CCD camera. Since the grid size is too small comparing to the image frame, the grid pattern is not clear in this figure. If we enlarge the image size grid pattern can be clearly seen on the monitor. The next step is to move the stage to allow the grid image clearly focuses on the spacer top. The distance of movement is equivalent to the spacer height. Fig. 9 plots the measured spacer profile, which result is the same as the one measured by a white light interferometer. The thickness of the color filter's RGB film can also be obtained in the same graph. The accuracy of this fiber bundle confocal microscope relies on the accuracies of the positioning stage and the characteristic curve of the grey level vs. focal distance. Current system is about 100nm. It is low cost and suitable for micro level measurements.

III. CONTACT MICRO/NANO PROBE

Ultrahigh precision 3D surface measurement technologies have been paid much attention in research during the last ten years. Although many non-contact measurement systems have been developed and commercialized successfully for meso to micron or micron to nano scaled 3D geometric measurement, such devices cannot cope with the side wall geometry measurement of high aspect ratio micro holes, grooves, and edges. The system design and integration of a contact type micro/nano-scale three dimensional coordinate measuring machines (3D CMM) has become increasingly important, and the development has thus emerged as a new research area due to the need of measuring micro parts. This kind of CMM requires higher measurement accuracy and resolution than conventional macro-scale 3D CMM. The design and manufacturing of the micro touch trigger probe becomes one of the critical factors to achieve the measurement capability [14].

A touch probe is composed of the probe stylus, the probe mechanism, and the sensor. The probe tip must be spherical with diameters ranging from 500µm to 100µm, or less. It is normally made by gluing a microball on a micro tungsten wire. The concentricity of the wire to the ball is a problem in assembly that will cause measuring error because the probe radius has to be compensated. A technique of fabricating monolithic probe stylus with melting and solidification processes of a thin glass fiber to form a micro-sphere tip has been developed by the authors, as shown in Fig. 10 [15]. This can assure the concentricity of the probe stylus. Two possible floating mechanisms and sensors that can integrate with the stylus are illustrated in Fig. 11, one is the detection of angular motion of the floating plate and the other idea is to detect the deformation of the suspension wires. The following will describe the developed probe system using the first concept.

Fig. 12 shows the proposed mechanism of a contact probe. The glass fiber probe stylus is fixed to a floating plate which is suspended by four evenly distributed wires connected to the probe case. The contact force will cause tilt motion of the plate and the wires will perform elastic deformation. Four mirrors mounted onto respective extended arms will amplify the up/down displacement at each mirror position. These displacements can be detected by four corresponding focus probes developed in this work, as described in section II A. The dimension of the mechanism can be simulated by finite element method to obtain optimum design. Because of the symmetrical geometry, the force-motion sensitivity should be symmetrical in X-Y plane. Fig. 13 shows the experimental setup for contact force calibration using two rotary index tables and one precision weigher with sensitivity to micro newton. Calibrated results are shown in Fig. 14 from which it can be seen that the forces are nearly balanced. The minimum contact force is about 50µN. The smallest probe radius so far can be fabricated is about 150µm. Further improvement to produce smaller ball tip will be conducted.

IV. CONCLUSIONS

This paper addresses the needs of probe technology for micro/nano measurements of meso/micro parts. Three kinds of probes have been developed, namely the focus probe, the confocal microscope, and the touch probe. Experimental results show that the point measuring focus probe by normalization technique can reach to 1nm accuracy but the range is small. Confocal microscope by fiber image bundle technique can measure area profile large vertical range but the accuracy is limited to 0.1µm at the present. The touch probe can measure side walls with minimum contact force of 50µN. For different measurement requirements we shall select proper probes.

ACKNOWLEDGMENT

The work reported forms part of a research program funded by the Tjing Ling Industrial Research Institute of National Taiwan University and the Natural Science Foundation of China (50420120134).

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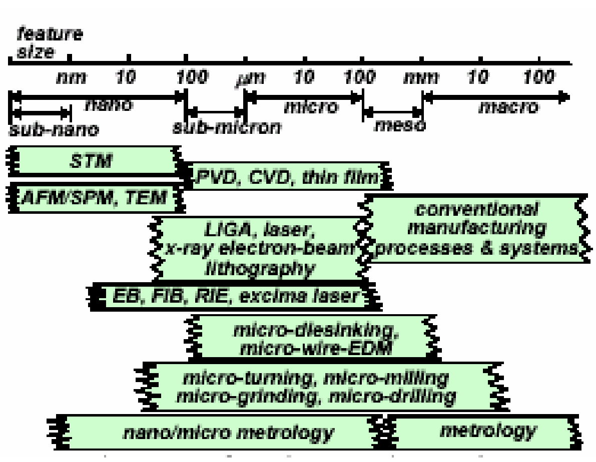


Fig. 1. Manufacturing at various scales

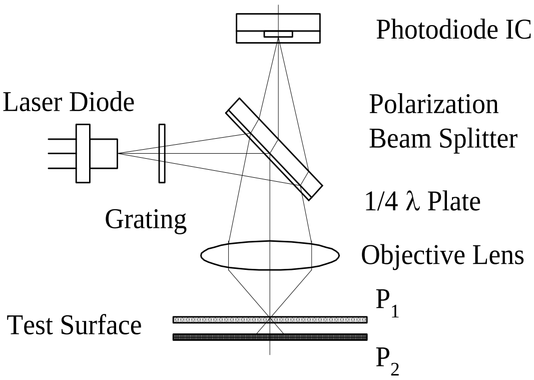


Fig. 2. Principle of focus probe

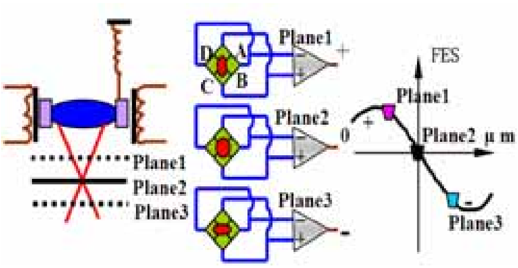
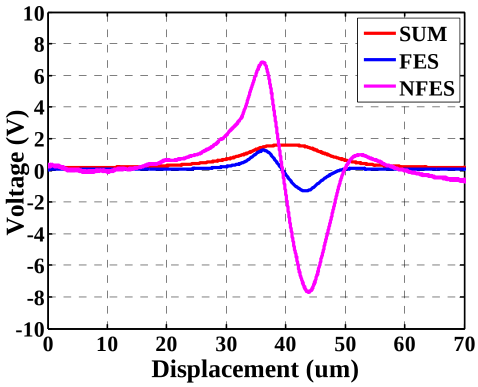
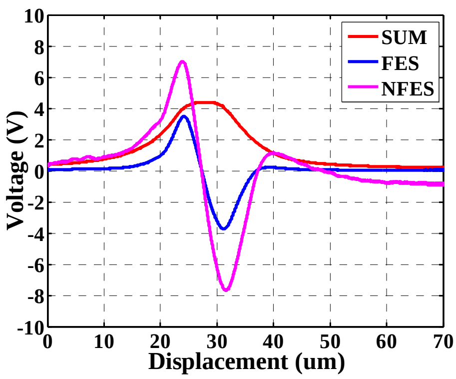


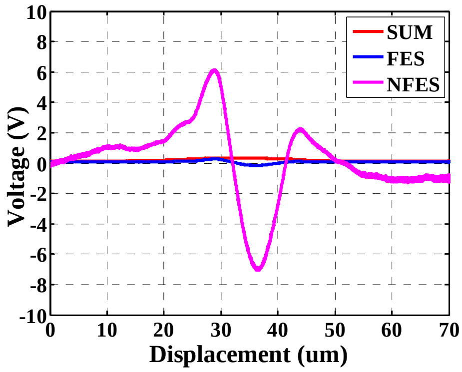
Fig. 3. The variation of spot shape with distance producing a S-curve of FES



(a) Silicon surface



(b) Mirror surface



(c) Nickel surface

Fig. 4. FES and NFES on various materials

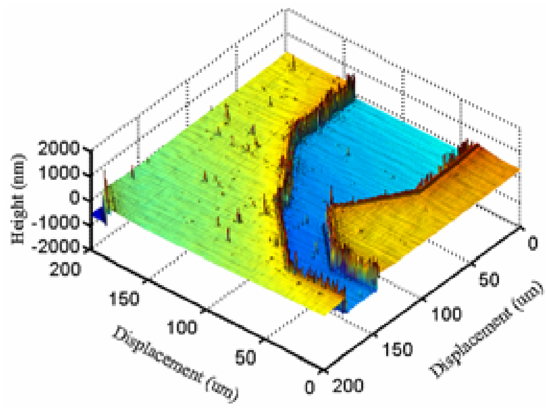


Fig. 5. Measured sample (Nickel on ALGaN)

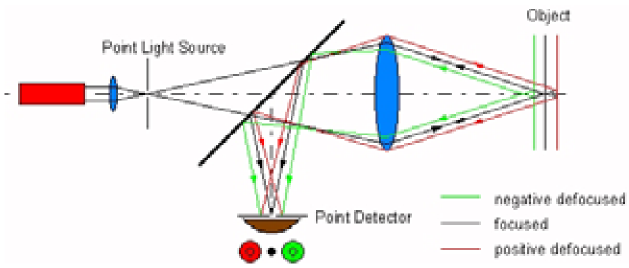


Fig. 6. Laser confocal probe

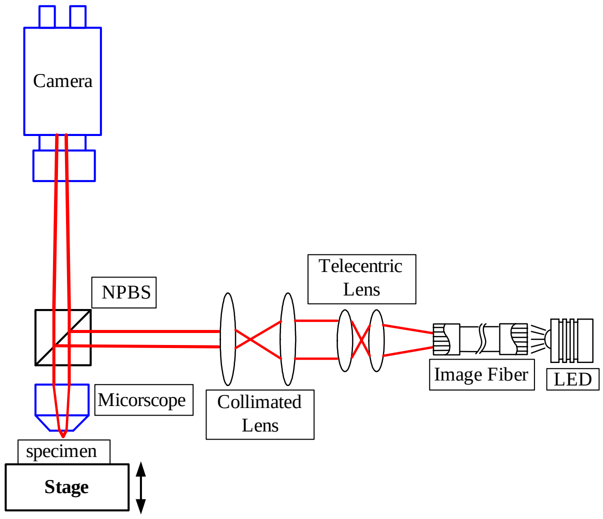


Fig. 7. Image fiber confocal microscope

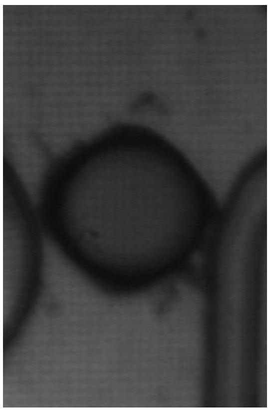


Fig. 8. Image shows focusing on the substrate of LCD spacer

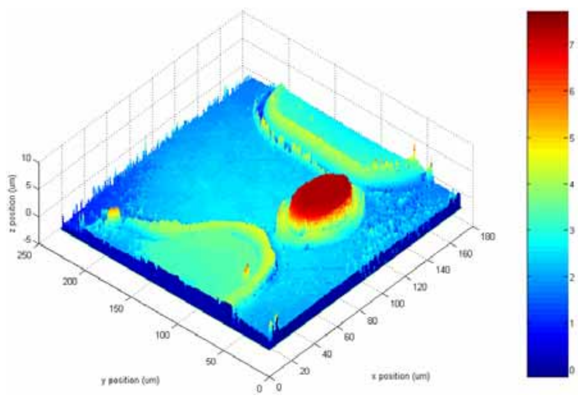


Fig. 9. Measured spacer profile by confocal microscope

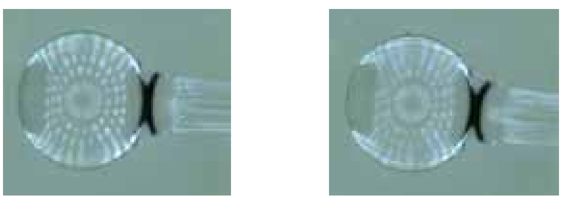


Fig. 10. Fabricated ball tips on a glass fiber

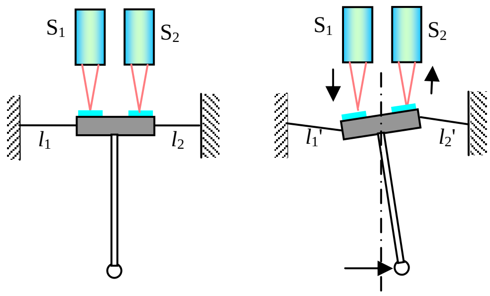


Fig. 11. Structure and motion of a touch probe

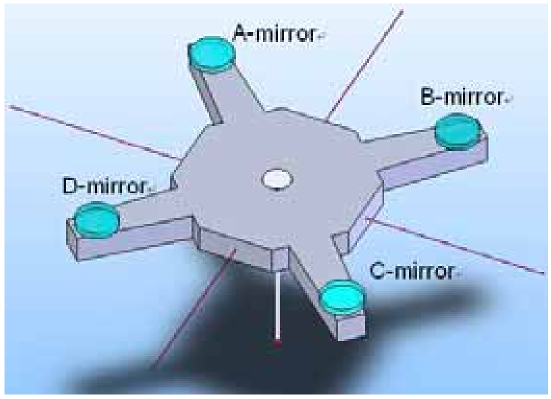


Fig. 12. Mechanism of the contact probe

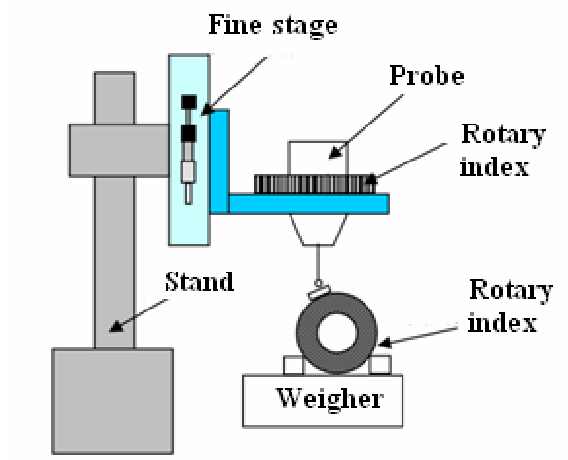


Fig. 13. Setup for probe calibration

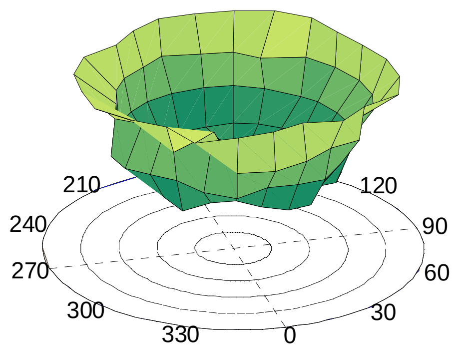


Fig. 14. Contact force distribution