A MULTI-SCOPIC 3D PRECISION MEASUREMENT SYSTEM FOR DEEP BLIND HOLES

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INTRODUCTION

Three-dimensional (3D) micro-structured surfaces have been widely used in the development of various products in different industrial fields to realize specially designed optical and mechanical functions, especially in PCB, semiconductor or LED industry, etc. However, the complexity of 3D-structured surfaces imposes considerable challenges for the control of the manufacturing process and quality assurance (QA), which makes 3D measurement to be indispensable. These related industries usually have extreme large production thoughput which requires the QA process to be high efficiency or even possibility to be performed real-time and in-process based on 3D measurement.

In the past decades, many high-precision coordinate measuring instruments have been developed [1] to perform 3D measurement. However, most of them are based on touch probe coordinate measurement principle with the use of the contact probe or non-contact optical probe. Contact-type CMM can provide high accurate measurement for various types of freeform surfaces, but the possible scratch marks caused by the contact between the probe and the measured surface is undesirable and unavoidable. Moreover, the measuring efficiency is rather low for mass production. In this sense, optical techniques [2] are widely used to develop a non-contact probe, such as light scattering techniques [3], fiber interferometry [4] and optical slope sensors [5], to measure the surface. They are reported as being capable of performing fast measurement of surface roughness and micro structures with nanometric accuracy. However, it is difficult to overcome the rigorous measurement requirements such as various surface structures, surface roughness or material, etc.

Multi-scopic technologies provide object space information with multi-perspectives through the use of microlens array (MLA), which is an emerging technology for the measurement of 3D micro-structured surfaces [6]. The multi-scopic 3D technology not only provides a compact system design but also allows the acquisition of snapshot data for high accurate reconstruction of 3D micro-structured surfaces under a shop floor environment.

Moreover, the conventional multi-scopic-based 3D reconstruction method encountered various limitations, such as heavy computation requirement [7], information loss [8], reduction of measuring resolution [9] or limited systematic compatibility [10]. Previous research study by the authors proposed a method in which the measured data are directly extracted based on disparity information (DEDI) of the captured images and processed through statistical analysis in order to have a precise match [11]. The precision and efficiency of this DEDI 3D information extraction algorithm are ensured to provide accurate final 3D measuring results.

In this paper, a multi-scopic measurement system is developed for the measurement of deep blind hole in PCB industry. It is interesting to note that holes are basic structure for PCB manufacture and the key dimensions of the hole includes lateral direction and depth information, which make 3D measurement to be a preferred solution. Since the quantity of holes on single board is very large and the nature of mass production, measuring efficiency is another key requirement. The developed multi-scopic 3D measurement technology is able to meet the demands of the user according to its fundamental theory. Experimental system is developed and fine-tuned accordingly for the measurement process of deep blind holes, which is the interim component during the PCB manufacturing process. Cross verification from ultra-precision offline metrology system shows that the measurement result from the proposed system achieve sub-micron accuracy.

MULTI_SCOPIC 3D MEASUREMENT SYSTEM

The multi-scopic 3D measurement method is a novel theory which has been proposed recently [8]. The raw 3D information of the to-be-measured surface is acquired in a single snapshot through a CCD camera and a micro lens array (MLA). The 3D digital model of the to-be-measured surface with the measuring data is precisely reconstructed through a system-associated DEDI method [11]. The multi-scopic-based 3D metrology system is capable of performing the in-situ measuring process of micro-structured surfaces, with sub-micrometer measuring repeatability under different measuring environments.

The basic principle of the multi-scopic metrology theory is shown in Fig. 1. It is divided into two processes which include a recording process and reconstruction process, respectively. Since the spatial positions of the elemental lenses vary, the acquisition of elemental images (EIs) have subtle differences which are referred to be disparities. These image points from different EIs which originate from a single object point are called corresponding points. The disparity of a certain point of the target that is located at a certain depth is quantitatively expressed by the parameters of the system setup and the variable of its depth information. The 3D information of the object space is retained in these disparities which are the carriers of the 3D information of the target that can be transferred to the reconstruction process. The disparity information can be represented by the number of pixels times single pixel size which are determined by the basic theory of machine vision-based measurement systems.

$$\frac{\Delta D^{(m,n)}}{(m,n)\times D_{EI}}=\frac{g}{SD} \qquad (1)$$

where $\Delta D^{(m,n)}$ is the disparity information; D_{EI} is the diameter of the EIs; m and n are the coordinate information of the elemental lens counting from the central one; g is the distance between the EIs and the MLA according to the system setup; and SD is short for the shooting distance which represents the depth information of the target point. The number of pixels and the to-be-measured value of the targets can be established in both the lateral and axial directions. The measured value along the lateral direction can be expressed as:

$$\frac{D_{sEI}}{D_l}\approx\frac{N_p\times p}{D_l}\cdot\frac{g}{SD} \qquad (2)$$

A quantitative relationship between where D_{sEI} D_{sEI} is the distance between two image points in a single EI as shown in the distance of two focused EI points of the red circle point and the blue square point in the n^{th} EI as shown in Fig. 1; SD is the depth information of the plane which is determined by the known disparity information; g is the distance between the EIs and the MLA according to the system setup, and D_l is the measured value of two target points as shown in the measured value between the two reconstructed image points (circle point and square point) in Fig. 1.

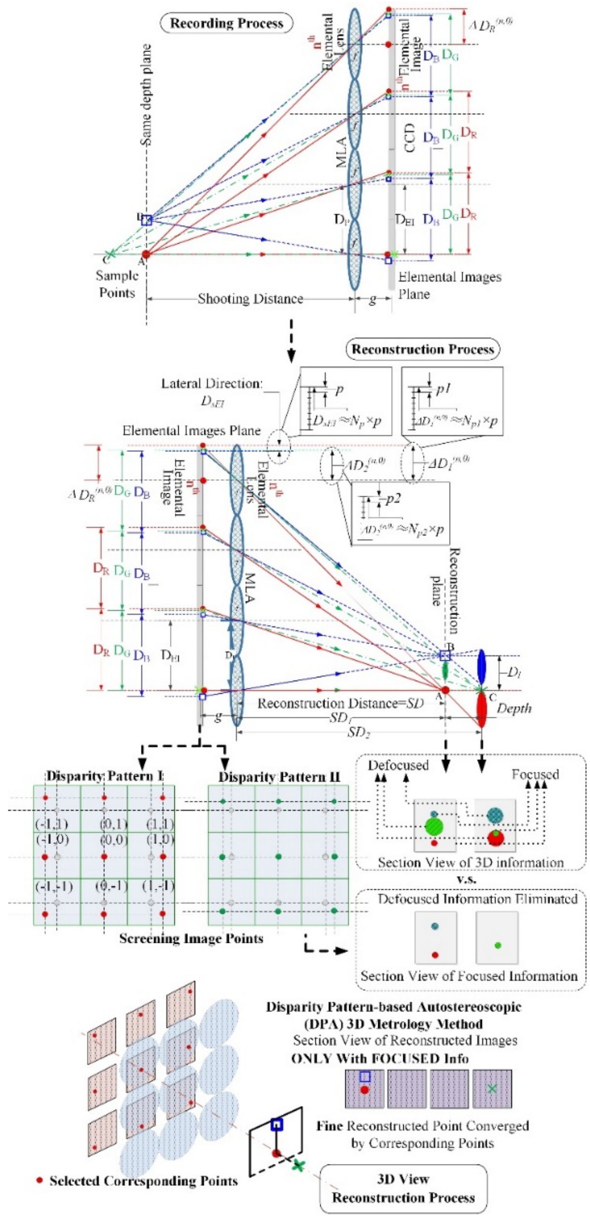

FIGURE 1. Basic science of the multi-scopic 3D measurement method

For the axial direction, the circle point A and the cross point C are used as a simple illustration. The distance between two depth planes, which is the measured value in the axial direction, is determined by Eq. (2) as follows:

$$SD_2 - SD_1 = gn\left(\frac{D_{EI}}{\Delta D_2^{(n,0)}} - \frac{D_{EI}}{\Delta D_1^{(n,0)}}\right) \approx gn\left(\frac{D_{EI}}{N_{p2} \times p} - \frac{D_{EI}}{N_{p1} \times p}\right) \quad (3)$$

where SD_1 and SD_2 are the abstract axial positions of two depth planes, which are shown in Fig. 1 as the depth plane of the circle point and cross point, n is the n^{th} EI; $\Delta D_1^{(n,0)}$ and $\Delta D_2^{(n,0)}$ are the disparity information of different depth information in the n^{th} EI which are shown as the disparity information of the circle point and cross point between the n^{th} EI and the central EI as shown in Fig. 1; g is also the distance between the EIs and the MLA according to the system setup, and the depth is the measured value between two depth planes in the axial direction.

The quantitative relationship in Eq. (2) and Eq. (3) satisfies the fundamental theory of the indirect metrology system. This is the theoretical foundation of the multi-scopic-based 3D measuring method. After obtaining the elemental images with 3D information recorded during the recording process, the disparity information is confirmed and extracted through a precision matching process of the corresponding points among the EIs so as to represent different depth information. Since every depth plane has its own focused information, which is represented by the corresponding points, the defocused information on every depth plane is eliminated as shown in Fig. 1. As a result, the 3D scene with lateral and axial digital information is fully reconstructed.

Based on the reversibility of the optic rays, the two processes become symmetrical by using the same micro-lens array (MLA) and system setup, which infers that the object space is precisely reconstructed with a scale that is not changed as shown in Fig. 1. This nature of multi-scopic theory is the foundation of the multi-scopic-based measurement method.

EXPERIMENTAL WORK

Based on the theory of multi-scopic 3D measurement method. A measurement system is developed for measuring deep blind hole with application in PCB industry. Fig. 2 shows the schematic diagram of the multi-scopic 3D measurement system which is composed of a CCD carmera working on visible spectrum, a microlens array with the scale of 20×20, LED white light source, and long working distance 10X objective lens from Mitutoyo.

An MLA is incorporated to a traditional microscope imaging system to provide multiple perspectives of the object scene. A 10X Mitutoyo long working distance objective lens is used as the main lens of the whole system. Axial illumination is also imported to the system through optical fibers and LED light source due to the 3D features of the micro-structured surface to be measured. The deep blind hole in PCB industry usually has a depth-to-diameter ratio which is equal to 1 or even smaller than 1. This provides great challenges to many 3D measurement methods and illumination style. Traditional side illumination is not applicable in this case because the micro-structure is deep which makes very little light transmit into the bottom of the structure.

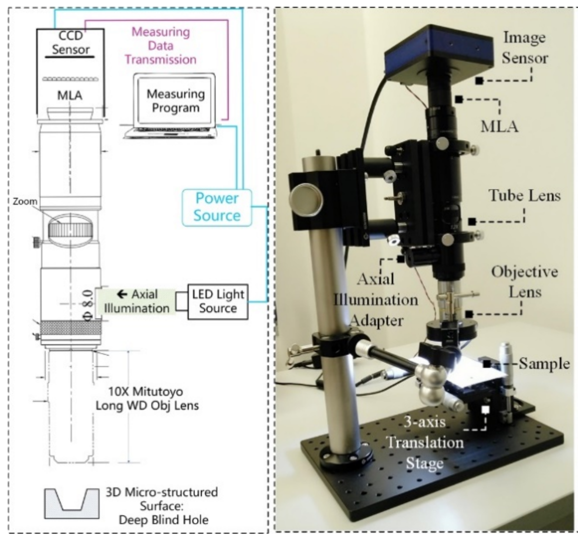

FIGURE 2. Schematic design and setup of the multi-scopic 3D measurement system for deep blind hole

Fig. 2 also shows the experimental setup of the proposed multi-scopic 3D measurement system. The raw 3D information of the target surfaces is acquired in a single snapshot through a CCD camera and a micro lens array (MLA). The 3D digital model of the target surface with the measuring data is precisely reconstructed through a system-associated direct extraction of disparity information (DEDI) method because the error is eliminated by statistical analysis used in the method.

Multiple measurements were conducted on a machined micro-structure of deep blind hole. As a kind of micro-structure which brings a lot of challenges to various measuring devices, the deep blind hole structure can be clearly reconstructed from the top to the bottom with the depth information through the proposed metrology system and associated data processing method as shown in Fig 3. An ultra-precision off-line measurement system Talysurf CCI is introduced to measure the same targeted blind hole of the sample in order to provide reference measuring data.

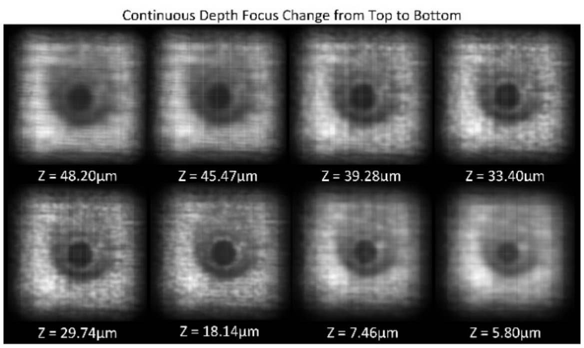

FIGURE 3. Reconstructed images of different depths of the deep blind hole

Table.1 shows the measurement results. The bias denotes the difference between the mean value of measuring data and reference value. Max. Abs. Err denotes the max absolute error comparing to the reference values during the repeat experiments. It is found that the system is capable of measuring deep blind hole surfaces with sub-micrometer measuring repeatability, comparing with the reference measurement data from Talysurf CCI as shown in Fig. 4.

TABLE 1. Summary of measurement results

Item	Dimension	Bias *(μm)*	Standard Deviation *(μm)*	Max. Abs. Err. *(μm)*
Sample 1	Top Radius	0.47	0.60	1.10
	Bottom Radius	0.23	0.50	1.13
	Depth	0.68	0.43	0.98
Sample 2	Top Radius	0.51	0.89	1.02
	Bottom Radius	0.35	0.63	0.81
	Depth	0.41	0.29	0.85

CONCLUSION

A 3D precision measurement system is developed for measuring deep blind holes with applications for PCB industry. The system is built based on multi-scopic measurement technology. Experimental studies not only verify the technical feasibilities in terms of accuracy and repeatability but also proved that the proposed system as a promising method for practical industrial metrology.

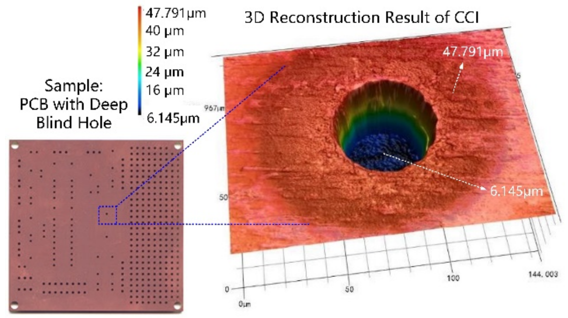

FIGURE 4. Sample and reference measuring data provided by Talysurf CCI.

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