Development of PMP system for high speed measurement of solder paste volume on printed circuit boards

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ABSTRACT

Non-contact measuring methodologies of three-dimensional profile using CCD camera are very attractive because of their high measuring speed and high sensitivity. When projecting a grid pattern over the object, three-dimensional information of the object can be extracted from the projected pattern image. Projection moiré using such a projected pattern image is used to extract 3D information with another grid pattern in front of CCD camera. As an alternative method to projection moiré, phase measuring profilometry (PMP) without such an additional grid pattern is used to obtain similar but improved results under practical measurement environment. This paper describes a new PMP technique with improved practicality. In this technique, three or more snapshots over object undergoing dynamic motion with respect to camera are all that is required to capture the 3D surface contour of the object. This technique is principally similar to the existing PMP techniques using multiple phase shifting images and it provides a similar resolution. However, this enables the contouring speed to be increased up to the frame rate of the camera because it is not necessary for object or camera to be in static during snapshot. Furthermore, it also makes contouring at a reasonable resolution and accuracy possible because very highly intensive light sources like LED or halogen can be used for high contrast. The principle of the technique is described and some preliminary experimental results are presented. Experimental results demonstrated the feasibility of the technique for high-speed surface profile measurement.

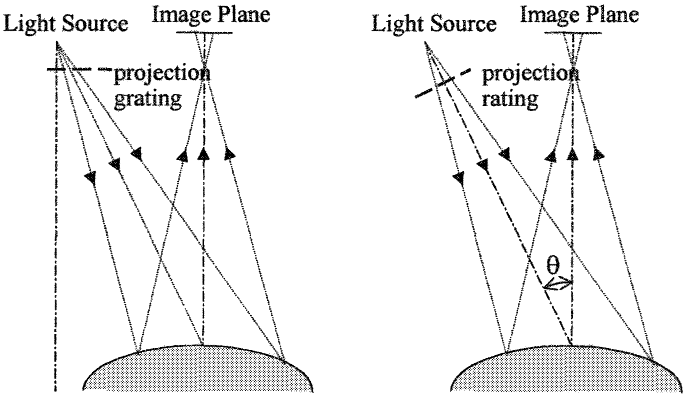
Keywords: 3D measurement, Moiré, Phase measuring profilometry, PMP, Solder paste inspection

1. INTRODUCTION

Although the development of 3D surface profile measurement systems has rapidly progressed by the continuing demand for improved methods of manufacturing industrial products, the 3D surface profile contouring still suffers from several problems of the accuracy, speed and cost not enough to be practically used. Extensive researches on the 3D surface measurement have been done in order to solve these fundamental problems. However, most early 3D surface measurement systems [1-6] have been proved still to yield several limited functionality and flexibility for the practical use.

Stereo vision of using two cameras is a conventional method of measuring 3D surface profile of objects. However, stereo is very computation intensive so that it is hard to be computed at a frame rates with the current state of the art. Range from focus is an alternative method for measuring 3D surface profile. But, the speed is also slow because many different focus settings must be used and at each focus setting, a new image must be captured and analyzed. Although time of flight and active triangulation can be used for 3D contouring of objects, they require scanning of the light beam to obtain a full frame of range image and so limit speed. To remove the need for scanning, 2D CCD camera can be used under the structured illumination, typically the projection of a pattern of light such as an array of dots, stripes, or a grid simultaneously onto the scene. However, such a method cannot achieve single-pixel resolution of the range image because processing information from a group pixel is required to determine the location of a structured light element in the image. Moiré techniques use some form of structured light, typically a series of straight lines in a grating pattern, which is projected onto an object in the scene. This pattern on the object is then viewed from some other angle through a secondary grating, presenting a view of the first grating line, which has been distorted by the contour of the part. The viewed image contains the moiré beat pattern, from which 3D contour of object can be extracted. However, determination of 3D contour requires both extensive data analysis and rigorous hardware manipulation to produce different moiré patterns of the same object. In addition, the variation in object surface reflectivity results in low accuracy by interfering with fringe formation. As an alternative method to the projection moiré, phase measuring profilometry (PMP) without such a secondary grating can be used to obtain similar but improved results under practical measurement environment undergoing variation in the surface reflectivity. The PMP shifts the first grating several times to make different phase-shifted patterns of the same object, where the grating should be shifted at least three times over static object. When the object surface to be measured is large as in case of the inspection of printed circuit boards, the PMP measurement head should scan over the entire board area by repeating the stop during the grating shifting and the move to the next measurement point. Therefore, the measurement system does not provide high-speed enough to inspect the printed circuit boards at the frame rate of the camera. Several techniques have been proposed in the past for high-speed 3D surface profile measurement. Harding [4] proposed a color-encoded moiré technique for high-speed surface contouring. Gang [5] developed a rainbow 3D camera, which can capture the 3D information of objects at the frame rate of camera. Huang *et al.* [6] proposed a color-encoded digital fringe projection technique, which allowed for the 3D surface contour information to be retrieved from a snap shot of the object. Zhang *et al.* [7] developed a new PMP technique in which a color fringe pattern generated by computer software is projected onto an object surface by using a commercial Digital Micro-mirror Device based video projection system. Some of these new systems proved to achieve a potential 3D shape measurement speed of up to the frame rates of camera. However, since color was used in all these techniques as the means to retrieve the 3D information of the object, measurement errors could be introduced by the original color of the object surface. Furthermore, some of them could not attempt any actual contouring of objects since the color pattern had a poor contrast ratio.

This paper describes a new high speed PMP technique and its application to real-time 3D inspection of solder paste on the printed circuit boards. As in the traditional PMP techniques, this technique also requires at least three images taken sequentially. In this technique, however, it is not necessary for objects to be in static during taking images. Three or more snapshots while object (or camera) moves are all that is required to capture the 3D surface contour of the object. However, every snapshot should be taken with synchronization to the relative position of object with respect to camera such that the consecutive snapshot images overlapped at regular intervals are made over the same object to make different phase shifting images. This technique is principally similar to the existing PMP techniques using multiple phase shifting and it provides a similar resolution. However, this enables the contouring speed to be increased up to the frame rate of the camera because it is not necessary for object to stop during snapshot. Furthermore, because very highly intensive light sources like LED or halogen can be used for this technique, fringe contrast is dramatically improved, and thus making contouring with this



(a) Parallel optical axes geometry (b) Crossed optical axes geometry

Fig.1 Parallel axis and crossed axes geometry technique at a reasonable resolution and accuracy possible. This paper describes the principle of this technique and presents some preliminary experimental results. The rest of this paper is organized as follows. Section 2 gives the principle and a full detail of the developed PMP system. Section 3 provides preliminary experimental results to demonstrate the usefulness of the developed technique. Finally, some conclusions are made in the last section.

2. OPTICS OF MEASURING DEVICE

2.1 Phase shifting projection Moiré method

The phase shifting projection Moiré method does not use the reference grid and the angle between reflection and camera optical axes is different from the conventional phase shifting interferometry. Fig.1 shows parallel axes and crossed-axis optic systems. In the parallel axes of Fig.1(a), to project a grid pattern on the front surface of an object to be measured, the reflection grid is much deviated from the center of reflection lens, but the geometry is easily analyzed. The conventional phase shifting interferometry is difficult to analyze due to use of the crossed-axes although it has a merit of using the reflective grid only.

2.2 Acquirement of deformed grid pattern

Fig.2 shows the optical system to create a grid pattern on an object to be measured and acquire its image using a CCD camera. The CCD camera can be modeled with a two-dimensional image sensor and pinhole lens model. The projection part consists of a light source and a projection grating. The camera optical axis is defined as a straight line crossing the center of lens and perpendicular to the surface of the 2D image sensor. The projection optical axis is defined as a straight line crossing the spot light source and perpendicular to the projection grating surface. The camera optical axis is parallel to the projection axis and perpendicular to a reference planar surface, which becomes a basis of measuring height of an object, *h*. Let f_c be the distance from the image sensor to the pinhole along the camera optical axis and L_c be the distance from the pin hole to the reference plane. Let f_p be the distance between the light source and the projection grating and L_p be the distance between the light source and the reference plane. The light generated from the source passes through a point x_g on the projection grating and arrives at a point $(x_0, h(x_0))$ on the object to be measured. When it is assumed that the

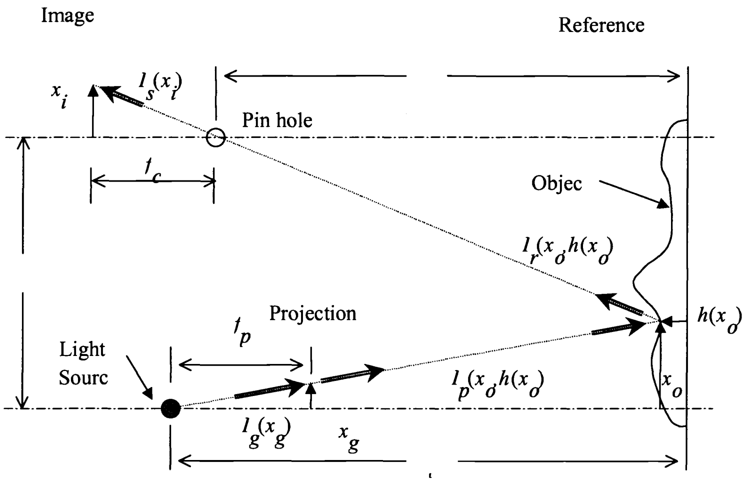


Fig.2 Optical geometry of grating projection

reflection light passes through the center of the pin-hole lens and arrives at x_i on the image plane of the CCD camera, the transparency of the projection grating, $T(x_g)$ can be described by the following cosine function with period of pitch g,

$$T(x_g)=1+\cos\left(\frac{2\pi}{g}(x_g+\Delta)\right) \tag{1}$$

where Δ denotes the initial position of the projection grating. If the light intensity at the point, x_g on the projection grating is $I_g(x_g)$, the intensity of the light at the point $(x_{0,}\ h(x_0)\ )$ on the object after passing through the projection grating can be derived as

$$I_p(x_{0,}\ h(x_0)\ )=I_g(x_g)[1+\cos\left(\frac{2\pi}{g}(x_g+\Delta)\right)] \tag{2}$$

and from the following geometric relationship,

$$\frac{x_g}{f_g}=\frac{x_0}{L_p-h(x_0)} \tag{3}$$

x_g can be described by

$$x_g=f_p\,\frac{x_0}{L_p-h(x_0)}. \tag{4}$$

Substituting Eq.(4) into Eq.(2) results in

$$I_p(x_{0,}\ h(x_0)\ )=I_g(x_g)\left[\ 1+\ \cos\left(\frac{2\pi}{g}\left(\frac{f_p x_0}{L_p-h(x_0)}+\Delta\right)\right)\right]. \tag{5}$$

The light intensity of a point, x_i on the image plane can described by the following equation,

$$I_s(x_i)=R\,(x_{0,}\ h(x_0)\ )\ I_p\,(x_{0,}\ h(x_0)\ ) \tag{6}$$

where $R\,(x_{0,}\ h(x_0)\ )$ is the reflectivity of a point on the object to be measured. From Eq.(5), Eq.(6) can be rewritten as

$$I_s(x_i)=A_i\left[\ 1+\cos\left(\frac{2\pi}{g}\left(\frac{f_p d}{L_p-h_i}-\frac{f_p}{f_c}\frac{L_c-h_i}{L_p-h_i}x_i+\Delta\right)\right)\right]. \tag{7}$$

Using the following geometric relationship,

$$\frac{x_i}{f_c}=\frac{d-x_0}{L_c-h(x_0)} \tag{8}$$

and the assumption of $L_p=L_c=L,\ f_p=f_c=f$, then $I_s(x_i)$ can be finally described by

$$I_s(x_i)=A_i\left[\ 1+\cos\left(\frac{2\pi}{g}\left(\frac{fd}{L-h_i}-x_i+\Delta\right)\right)\right] \tag{9}$$

where $A_i \equiv R\left(x_{0,}\ h(x_0)\right) I_g\left(x_g\right)$.

If $h_i \equiv h(x_0)$, Eq.(8) can be

$$\frac{fd}{L-h_i}-x_i=\frac{fd}{L-h_i}-\frac{fd}{L}+\frac{fd}{L}-x_i=\frac{fd/L}{L-h_i}h_i+(\frac{fd}{L}-x_i)\cdot \tag{10}$$

From Eq.(10) and $\frac{fd}{L}-x_i=x_i^{'}$, we can derive

$$I_s(x_i)=A_i[\ 1+\cos(\ \frac{2\pi}{g}(\ \frac{\frac{fd}{L}h_i}{L-h_i}+x_i^{'}+\Delta\ )\ )\ ]\cdot \tag{11}$$

From Eq.(10), it can be known that the light intensity, $I_s(x_i)$, which is acquired by the image sensor varies according to the height of the measuring point, h_i. Under the assumption of $L >> h_i$, we obtain

$$I_s(x_i)=A_i[1+\cos(\frac{2\pi}{g}(\frac{fd}{L^2}h_i+x_i^{'}+\Delta))]\cdot \tag{12}$$

When the object to be measured moves in x direction and a point, x_i at the image plane change to $x_i+x_\delta(\equiv x_{i+\delta})$, Eq.(12) can be rewritten as

$$I_s(x_{i+\delta})=A_{i+\delta}[1+\cos(\frac{2\pi}{g}(\frac{fd}{L^2}h_{i+\delta}+x_{i+\delta}^{'}+\Delta))]\cdot \tag{13}$$

The assumptions of $A_{i+\delta}=A_i$, $h_{i+\delta}=h_i$ and $x_{i+\delta}^{'}=x_i^{'}+mg+\gamma$ where m is integer number and $0<\gamma<g$ yield

$$I_s(x_{i+\delta})=A_i[1+\cos(\frac{2\pi}{g}(\frac{fd}{L^2}h_i+x_i^{'}+\gamma+\Delta))]\cdot \tag{14}$$

By the four-bucket algorithm[8], we can obtain the phase of the reference plane, ϕ_{ri} as the following equation,

$$\phi_{ri}\equiv\frac{2\pi}{g}(x_i^{'}+\Delta)=\tan^{-1}(\frac{I_{r1}-I_{r3}}{I_{r0}-I_{r2}}) \tag{15}$$

where I_{r0}, I_{r1}, I_{r2}, and I_{r3} are the intensity values of the reference plane, $h=0$ without the measurement object for $\gamma=0, g/4, g/2, 3g/4$, respectively. Furthermore, by the four-bucket algorithm, we can obtain the phase of the measurement object, ϕ_{oi} as the following equation,

$$\phi_{oi}\equiv\frac{2\pi}{g}(fd\frac{h_i}{L^2}+x_i^{'}+\Delta)=\tan^{-1}(\frac{I_{o1}-I_{o3}}{I_{o0}-I_{o2}}) \tag{16}$$

where I_{o0}, I_{o1}, I_{o2}, and I_{o3}, are the intensity values of the measurement objects for $\gamma=0, g/4, g/2, 3g/4$, respectively. From Eqs.(15) and (16), the phase difference between the reference and the object becomes

$$\phi_{oi} - \phi_{ri} = 2\pi \frac{fdh_i}{gL^2}, \tag{17}$$

and from Eq.(17), the height of the object are finally determined by

$$h_i = \frac{gL^2}{fd} \frac{\phi_{mi}}{2\pi} \tag{18}$$

where $\phi_{mi} = \phi_{oi} - \phi_{ri}$.

Furthermore, the phase, ϕ_{mi} can be described by

$$\phi_{mi} = \overline{\phi_{mi}} + 2\pi m \tag{19}$$

where $\overline{\phi_{mi}}\left(-\pi < \overline{\phi_{mi} \le \pi}\right)$ is measurable overlap phase and m is an integer value. In case of object with large height variation, phase unwrapping process is used where the continuity of height value is assumed.

3. EXPERIMENTAL RESULTS

In order to evaluate the technique for phase measurement, we perform a series of experiments. Fig.3 show the experimental setup. We used a SONY XC-75 CCD camera and a S6X11 zoom lens. The Matrox Meteor-II with resolution of 640x480, was used for image grabbing process. The grating has a pitch, *g,* of 0.92mm, which was made of a crystal panel printed by semiconductor lithograph process to produce fine grating patterns. As a light source, the halogen lamp was used and a precision x-y table was used for movement of the object to be measured. By using a standard phase unwrapping algorithm, a continuous phase map representing the 3-D structure is obtained. With calibration, the phase map can be further converted to x, y, z coordinated values. Fig.4(a) and (b) show images of grating projected to the reference plane and a rectangular type 3D object, respectively. Fig.4(c) and (d) show the intensity map representing the phase, ϕ_{oi} and the phase

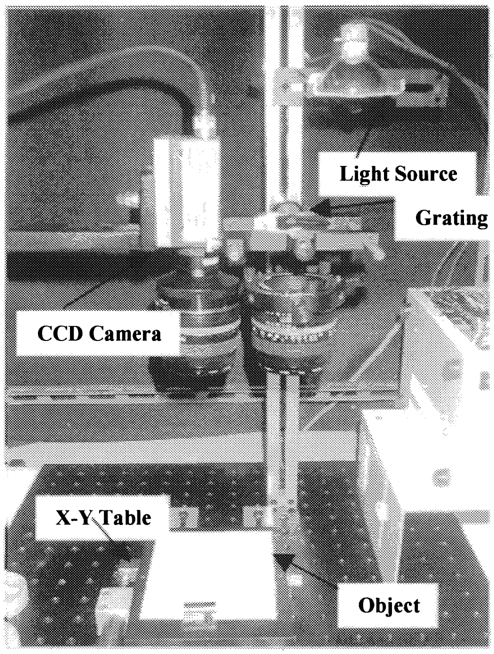


Fig.3 Experimental setup

difference, ϕ_{mi} obtained from four images of the object moving in x-direction. Fig.5(a) shows a phase profile for a pixel coordinate in image plane and Fig.5(b) shows the 3D phase map reconstructed from continuous phase profiles. With calibration, the phase map can be further converted to x, y, z coordinated values. Fig.6(a) shows the results of the experiment repeated for a solder pasted board shown Fig.6(b).

4. CONCLUSION

The PMP technique presented in this paper does not require object or camera to be in static during snapshot. Therefore, contouring speed is limited only by the frame rate of the camera, and it means that if a standard CCD camera is used, contouring speed up to 60frame/sec can be achieved. This contouring speed is difficult to attain by the traditional sequential phase-shifting techniques. Furthermore, because very high intensive LED or halogen lamps can be used as light source for pattern projection, it is possible for the contouring to be achieved at a reasonable accuracy and resolution. Therefore, this new technique should be especially useful in contouring objects that are under dynamic motion or in inspecting the solder paste on the printed circuit board.

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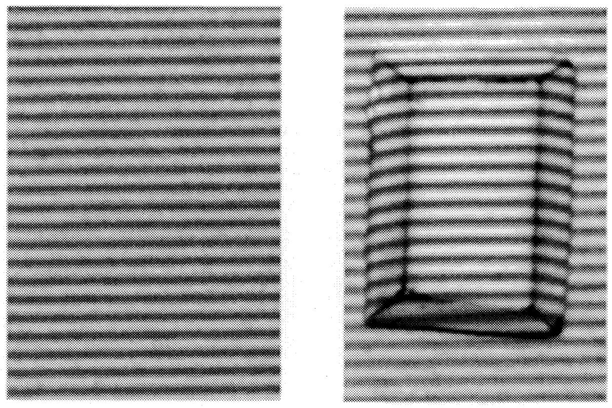
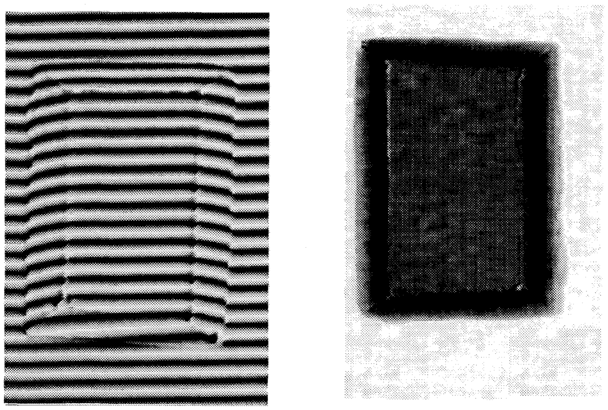
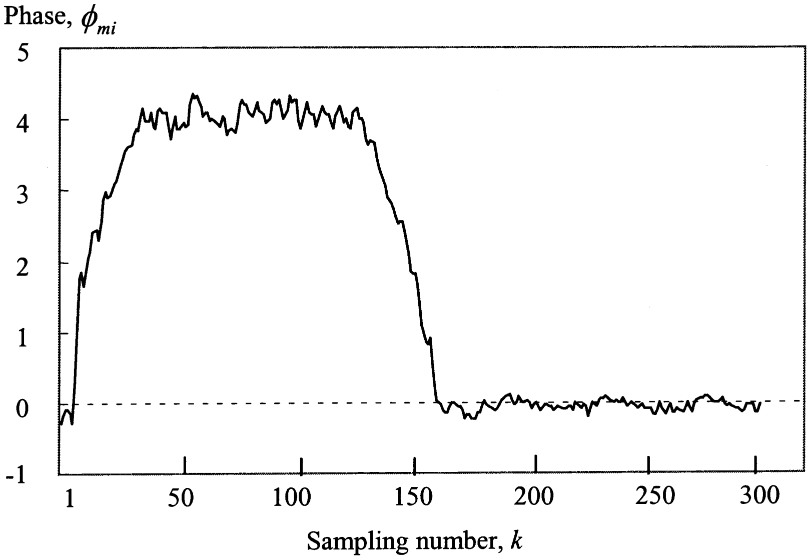


(a) Reference image (b) Object image

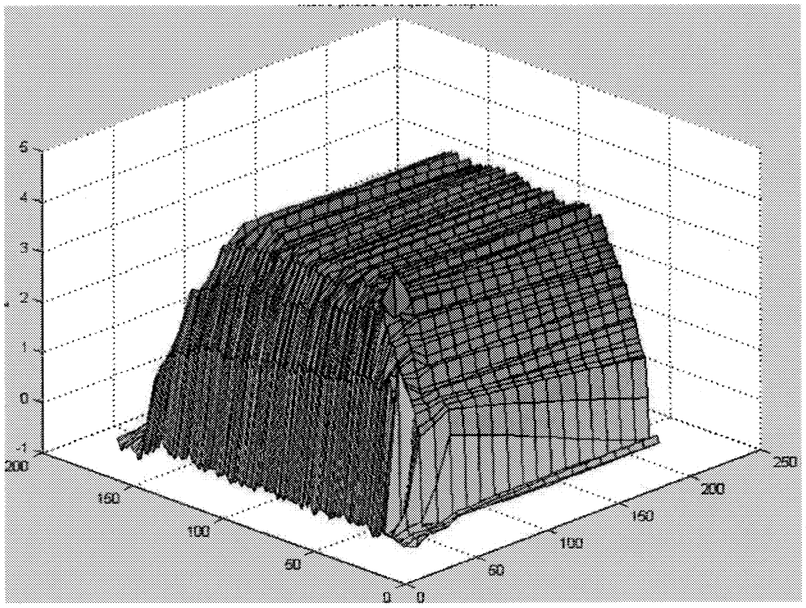


(c) Object phase (d) Phase difference

Fig.4 Experimental result for a rectangular object

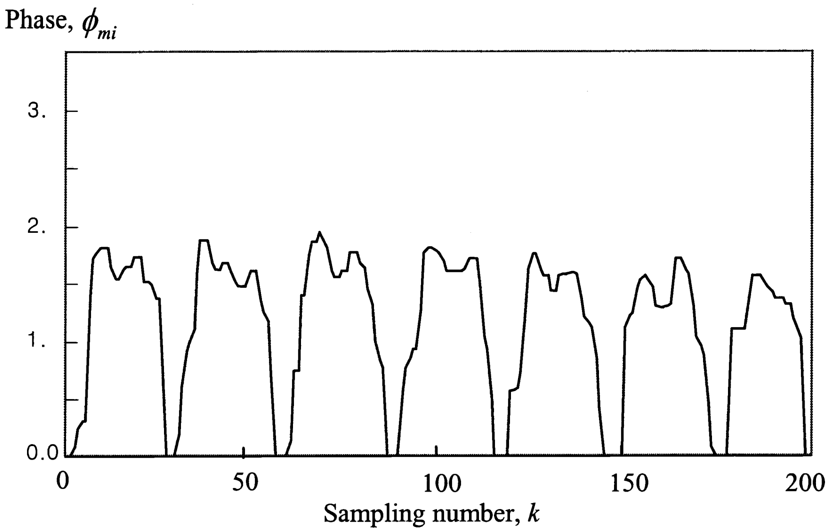


(a) Phase profile after unwrapping

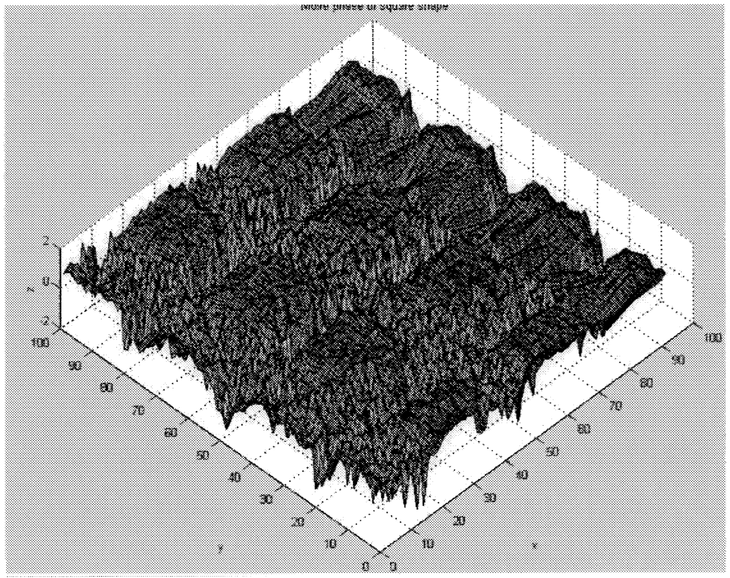


(b) 3-D reconstruction of the object

Fig.5 Experimental result of shape measurement



(a) Phase profile after unwrapping



(b) 3D reconstruction from phase profiles

Fig.6 Experimental result for a solder paste of PCB

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