3-D Surface Profilometry for Objects Having Extremely Different Reflectivity Regions

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Abstract: A novel surface profilometry method is proposed to overcome a difficult surface measuring problem when encountering a measured surface simultaneously having specular and scattering reflective conditions. Most moiré projection scanning methods effectively work on scattering or diffusing reflectivity objects, in which it assumes the object emitted light to be well captured by optical sensors. However, in reality, this assumption does not stand anymore when measuring a surface possessing both scattering and specular conditions. Therefore, to resolve the problem, the proposed method proposes a novel dual optical sensing configuration by employment of two optical sensors with two different viewing angles, in which one captures scattered reflective light and while another detects specular surface light with respect to the surface for achieving simultaneous full-field surface profilometry. The measured deformed fringes from both the sensors can be further transformed to 3-D depth information and merged together for full-field surface reconstruction. Some calibration targets and industrial objects were measured to verify the feasibility and accuracy of the developed method. The experimental result shows that the method can effectively overcome the above-mentioned problem. The measurement repeatability with one standard deviation can be controlled less than 0.3 and 2.0 μm, respectively for specular and scattering surfaces simultaneously. The method provides a significant advance in in-situ automated optical inspection (AOI).

Keywords: Scattering surface, specular surface, moiré projection, 3-D measurement, automated optical inspection (AOI).

I. Introduction

Measuring 3-D profile of object surface is increasingly becoming important in our life particularly in industrial inspection. 3-D surface measurement can be generally classified in two major categories as tactile and non-contact conditions. Coordinate Measuring Machine (CMM) is one general system that uses surface contact tactile and non-contact techniques to measure 3-D profiles. Tactile sensing cannot accurately measure soft object surfaces and the probe may potentially scratch or deform the measured surface. In contrast, non-contact methods can be effective to measure surfaces with high spatial resolution and useful for soft objects. Among these, optical triangulation methods, such as stereo vision, laser scanning and structured light methods, are widely used in industries. However, the optical methods often require uniform surface light reflection condition to ensure reliable sensing. Without this achieved, it generally becomes rather difficult for using optical triangulation methods to measure a surface possessing both scattering and specular conditions.

One of the significant challenges in optical surface measurement lies on dealing with reflectivity variations of the object surfaces underlying testing. Measuring objects having high reflectivity variations, such as highly shiny or scattering surfaces, is a critical issue to automated optical inspection (AOI) in ensuring measurement accuracy and product quality assurance. Poor 3-D measured result is widely common when encountering high surface reflectance variances on surface to be tested or reconstructed for 3-D printing or other purposes.

One of the popular 3-D optical surface measurement methods is structured light projection, which is widely employed in industrial testing applications. The method basically works based on triangulation measurement principle with an assumption on the tested object to have uniform light reflectivity for ensuring capture of the deformed fringe reflecting from the tested surface. However, in reality, the assumption may often fail while facing high reflectivity variations on the surface. For example, most industrial IC chips are fabricated with a silicon substrate with an extremely shiny surface and are also embedded with metal bumps having a scattering surface reflectance. Therefore, under such a condition, the reflected lights from the tested surface are rather complex, with its reflected light emitted to all different direction, in which the detecting sensor cannot receive the phase information accurately for reconstructing surface morphology.

In literature, several methods have been proposed to resolve the problem when measuring on specular targets. All these methods effectively reduce specular effects in different degrees but cannot resolve the problem completely. One the technique was proposed to separate specular component from diffuse component and filter out the specular component using polarizers [1]. Other methods, such as using the multi exposure time [2] or projecting special structured light with strip edges [3]. Fringe reflection is also a powerful measurement technique to measure shiny object’s surface [4]. This technique is based on the optical path difference to generate a deformed fringe pattern following the basic light reflection principle. To measure a specular object’s surface, the fringe pattern can be projected on a diffuse flat plane (or curvature) to generate diffuse light patterns as incident fringe projection. The diffuse pattern is reflected on the shiny surface and detected an optical sensor due to multi reflected beams. The distorted fringe pattern being detected can carry the phase information representing the surface’s depth. As a result, the object surface can be reconstructed by using phase gradients detected from the sensor.

However, up to date, the most existing methods discussed above can resolve the light specular problem.

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only for a surface with uniform reflectivity. When the object surface reflectivity is non-uniform, the captured image contrast becomes poor or even non-detectable. Thus, these existing measuring techniques are not effective to overcome the complex reflectivity problem encountered in optical surface profilometry. This critical problem has to be further resolved.

II. Statement problem

A. Extremely various surface reflective conditions

There are many industrial parts having the reflective condition to be inspected for its dimensional compliance. For example, industrial semiconductor components usually contain several different elements such as body (epoxy, silicon, etc.), metal bumps and pads (lead, solder, etc.). In there, each element may have a very complicated shape with various orientations with respect to the detected optical sensor. Moreover, the most challenging task is to tolerate extremely surface light reflectance variance ranging from diffuse (or scattering) to specular (mirror-like) of an element to be tested. The 3-D optical surface profilometric method of the tested objects normally projects any form of structured light pattern with the assumption that non-absorbent and perfect diffusely scattered model of measured surface is observed. In triangulation detection, viewing the measured target from a sensing angle pose a huge uncertainty which depends on the surface reflectance property. The quality of the fringe detection for phase reconstruction determines success of the surface reconstruction. Therefore, a new and effective technique is really necessary for accurate surface profilometry on the surface with this kind of the reflectance variance.

In the structured fringe projection, the angle between the projection and the sensing detection plays an important role. For inspecting a laser grove being fabricated on a wafer surface,

Fig. 1(a) shows the captured fringe image when the viewing angle is near zero. The groove area shown is rather clear but the rest wafer area is almost non-detectable. When the angle is increase, the reflected light becomes a mixed light containing diffuse and specular reflectance (see Fig. 2). Therefore, the groove area can be seen with a long exposure time because of diffuse light becomes weaker and the reflected light from the wafer flat surface becomes stronger. When the viewing angle becomes larger, the wafer surface becomes clearer with a better image contrast (see

Fig. 1(b) and (c)).

Fig. 1(d) is the transition stages when the viewing angle is increased. When the reflectance relation follows the light reflectance rule, the fringe contrast on the wafer surface reaches to its maximum and it can be illustrated as

Fig. 1(e).

Fig. 1(f) represents the case when the sensor is over saturated by a long exposure time. Figure 1 clearly describes the critical condition of the surface reflectance of the tested surface underlying inspection.

B. Existing technical difficulty

A major challenge of 3-D scanning techniques is the presence of specular reflectance on the test object surface.

Specular highlights occur on object surfaces where the specular component of reflection from illumination of light sources is dominant, in which the specular reflection almost obscures details of the tested object surface. Specular highlights are common artifacts of most lighting environments and are not part of the intrinsic visible detail of an object surface. In addition, specular highlight can easily saturate the detected image for no information being detectable.

Several approaches were proposed to separate the specular reflection using color analysis [5], [6] or polarization analysis on reflected light [7] or using environmental structured illumination [8]. Many existing techniques using light property analyses intended to separate reflectance component of reflected light by proposing three major principles: color based techniques [9], a combination of polarization and color based techniques [10], neighborhood (pixel or temporal) based techniques [11], or using environmental structured illumination [12]. Although these methods claim some success in overcoming the issue, these methods are based on some assumptions either on uniform surface reflectance or special surface light reflectance conditions, which are not totally applicable for in-situ AOI application.

III. Research Methodology

A. Optical system setup for surface profilometry
Fig. 3 illustrates the optical system configuration of the developed 3-D inspection system. As can be seen, it includes a light source (1), a diffuser (2), which is collimated by a lens module (3) and a sinusoidal grating (4) and a linear translator 5 for generating an accurate shifted phase.

In the system, the structured light generated by the incident optical module passes through a telecentric lens (6) and is projected onto the measured surface (8) defined by the reference plane (7). The reflected light passes through two lenses (12 and 13) and is captured by two individual optical sensing cameras (10 and 11). When the projected sinusoidal fringe (9) hits the measurement surface, it becomes a deformed fringe due to the phase difference generated by the optical path difference (OPD) between the object profile and the reference plane. The deformed fringe image is transferred to a computer (14) and the phase map is then computed by multi-phase shifting and wrapping principle by using a set of deformed fringe images. As a result, the phase unwrapping and phase-to-height transformation is performed to extract the profile of the measured surface.

B. Measuring Principle

B1. Phase shifting technique

The basic procedure of the 3-D shape measurement using digital fringe projection method includes projecting a sinusoidal fringe pattern onto the object, taking the image of the object illuminated with projected fringes, and then calculating the height information of the object through phase-shifting, phase unwrapping and phase to height transformation processes. Finally, 3-D coordinate transformation is applied to transform the phase-height information to physical point coordinates \((x, y, z)\) of each detected measured point. In phase-shifting algorithm, the phase \(\phi(x, y)\) is computed by the light intensities set by different phase-shifting of fringe grating projected by at least three channels. For the 3-step phase-shifting method, intensities of the three channels in each pattern can be modeled as follows:

\[
I_1(x, y) = I_a(x, y) + I_m(x, y) \cos[\phi(x, y) + \delta_1] \tag{1}
\]

where \((x, y)\) is the pixel location, \(\phi(x, y)\) is the phase value used by phase-shifting algorithm, \(I_a(x, y)\) are the intensities of the four pictures measured for each pixel position, \(\delta_1\) is the phase shift, \(I_1(x, y)\) and \(I_m(x, y)\) are the average intensity and the intensity modulation for each pixel. The expression of \(\phi(x, y)\) can be resolved from Eq. (1) as:

\[
\phi(x, y) = -\tan^{-1}\left[\frac{\sum_{k=1}^{N} I_1(x, y) \sin(\delta_k)}{\sum_{k=1}^{N} I_1(x, y) \cos(\delta_k)}\right] \tag{2}
\]

where \(\delta_k, k = 0, 1, 2, \ldots, N\), are the phase-shifting values of each channel. For the 4-step phase-shifting method, \(N = 4\), and \(\delta_1 = 0^\circ, \delta_2 = 90^\circ, \delta_3 = 180^\circ, \delta_4 = 270^\circ\). Thus, the phase value \(\phi(x, y)\) can be computed by the intensities of all channels and corresponding phase-shifting \(\delta_k\) from the 4-step phase-shifting method shown in Eq. (2).

Since the definition of the phase value \(\phi(x, y)\) is an arctangent function, a principal phase value can be obtained in a range from 0 to \(2\pi\) for phase wrapping. Therefore, if the pixel-based phase difference is larger than \(2\pi\), the wrapping phase becomes discontinuous and ambiguous. To obtain a continuous phase map, a process to add or subtract the multiple values of \(2\pi\), so-called phase unwrapping, is needed to reconstruct the non-ambiguous phase map.

The traditional phase-to-height transformation is introduced by the triangulation method. The objects height...
of each pixel can be uniquely represented by phase \( \phi(x,y) \), the phase difference between the measured object and the reference plane. Therefore, the object height has an approximately linear relationship with the phase difference as shown in Eq. (3) when some measuring assumptions are satisfied. Thus, the phase value can be transformed by a linear transformation coefficient \( K \), and then the object height information is given as:

\[
h(x, y) = K \phi(x, y)
\]

B2. Innovative dual sensing technique

As mention above, when the projected light beam hits the tested surface, the reflected light beams may contain diffuse and specular components (see the Fig. 2). The diffuse component is mainly formed by reflected light beams from micro structures with certain level surface roughness. Each reflected beam can be interfered with other beams. Fortunately, the light source is of low coherence and the light interference is not possible. Consequently, the diffuse light intensity can be reflected with a certain reflecting angle and can be detected by a co-axial sensing camera. In a different way, the specular light is generated by the reflection of incident light from an object surface with shiny reflective condition and normally in a low surface roughness condition. According to law of reflection, the reflected light beam angle is equal the incident light beam’s one. Therefore, the specular light can be detected by an optical sensing camera locating with an equal reflectance angle with respect to the incident light.

To capture both specular and diffuse components simultaneously, the idea of using a novel dual sensing optical is employed. In the configuration, one camera is dedicates to capture the specular component while another one is employed to capture the diffuse component. To reconstruct 3-D shape of the measured surface, the reflected fringe images representing specular and diffuse beams are simultaneously captured by the proposed system, illustrated in Fig. 3. By controlling adequate level of light exposure times required by the individual cameras, two deformed fringe images can be detected with high image contrast. The whole 3-D shape of the measured target surface can be effectively synthesized from two individual image detection and reconstructed by an accurate pixel spatial mapping between two sensors.

IV. Experimental results

To demonstrate the feasibility and measurement performance of proposed technique, a 3-D measurement system consisting of two sensing cameras, a single-frequency transmission grating having a period of 24 lp/mm, a step motor with accuracy less than 1 µm was developed. Two the same telecentric lens are employed in front of two cameras to collimate the reflected light projection on the measured object surface. The light module is powered by a 30 Watt white light LED, in which the LED is mounted on a special designed mechanical radiator for heat diffusion. To fulfill its engineering application, a SolidWorks design of system and its hardware system are implemented and shown in Fig. 4(a) and (b), respectively.
Fig. 5 Measurement results of the wafer sample shown in Fig. 1: (a) captured image of tilting camera; (b) captured image of co-axial camera; (c) wrapped phase map from tilting camera; (d) wrapped phase map from co-axial camera; (e) cross section on wrapped phase map of the tilting camera; (f) cross section on wrapped phase map of co-axial camera; (g) flat area wafer’s 3-D shape measured by the tilting camera; (h) groove wafer’s 3-D shape measured by co-axial camera; (i) 3-D shape of wafer after mapping the co-axial and tilting camera measurements.

Fig. 5(a) and (b) illustrate the captured images from the tilting and co-axial cameras of the wafer target being tested in Fig. 5(c) shows the phase map of wafer which is measured by the tilting camera, which captures the specular light reflecting from the flat wafer surface. Fig. 5(e and g) show the phase map and one cross section of the crossed groove detected from the specular wafer surface. Please note that the 3-D measured shape area of the groove region has random noises due to the non-detectable diffuse light from the laser groove surface region. Fortunately, this region can be totally recovered and reconstructed by another co-axial camera which can capture the diffuse light from the groove region. By doing so,, Fig. 5(d) and (f) show the phase map and one height cross section reconstructed by the co-axial camera. The groove surface region can be well measured and reconstructed (see Fig. 5(h)). Two 3-D detected shapes from Fig. 5(g) and (h) are mapped by the calibration method and merged to become a full-field 3-D shape of the measured wafer, shown in Fig. 5(i). The whole wafer 3-D surface shape can be accurately measured and reconstructed by using the developed technique.

Fig. 7(h) shows the 3-D shape of IC chip’s surface after mapping measurements of two cameras. The 3-D shape on substrate areas are smooth as measurement in Fig. 7(e) and the shooting noises on pad areas are replaced by the detected signal from the co-axial sensor. The measurement result indicates that the measuring difficulty and problem discussed in the earlier session can be well resolved. In-situ full-field 3-D optical surface profilometry on a measured surface with an extremely surface reflectance variance can be achieved by the developed method.

Meanwhile, Fig. 6 exhibits the measured height cross section along one lateral cross section on the wafer being captured by the tilting and co-axial camera. The standard deviation of flat wafer areas and groove area are evaluated for measurement accuracy. In a 30-time repeatability test, the standard deviation in the meaningful detection data regions shown in Fig. 6(a) and (b) are 0.265 µm and 1.937 µm, respectively. This shows that the measurement repeatability can be achieved for less than 2.0 micrometers when measuring a rough laser machining surface on wafer.

Fig. 6 Height cross section of Column 400 on wafer in Fig. 5: (a) captured by tilting camera; (b) captured by co-axial camera; (c) mapped co-axial and tilting camera data by proposed technique.

Fig. 7 Measurement results of industrial IC chip: (a) captured image of tilting camera; (b) captured image of co-axial camera; (c) wrapped phase map from tilting camera; (d) wrapped phase map from co-axial camera; (e) cross section on wrapped phase map of tilting camera; (f) cross section on wrapped phase map of co-axial camera; (g) IC chip’s 3-D shape is measured by tilting camera; (h) IC chip’s 3-D shape is measured by co-axial camera; (i) measured ROI of industrial IC chip; and, (j) 3-D shape of measured ROI in (i).
Similarly, Fig. 7 shows the measured results on a part of industrial IC chip (see Fig. 7(g)). Fig. 7(c) and (e) show the phase map and one cross section on it. In this measurement, using the traditional fringe phase-shifting method, the high reflectivity part is the wafer substrate that can be measured without any problem.

However, many measured noise exist on the IC chip’s pads (see the 3-D shape in Fig. 7(h)). By using the developed method, the measurement of IC chip can be successfully achieved, in which both the pad and substrate areas can be well reconstructed and shown in Fig. 7(i) and (h). A significant improvement is obvious before and after the method was employed in this case study.

V. Conclusions
In the article, a new dual sensing measuring method for 3-D surface profilometry is developed successfully to deal with a difficult problem in measuring an object with various surface regions having extremely surface reflectance variance. The developed technique is based on a new optical configuration to simultaneously detect specular and diffuse light reflected from various surface regions on the tested object. Again, an important calibration is proposed to merge 3-D shape of separate object surface regions seamlessly for achieving accurate surface profilometry. The experimental result indicates that the proposed method can effectively resolve the existing problem for achieving simultaneous measurement repeatability of one standard deviation to be less than 0.3 µm on a specular surface and 2.0 µm on a scattering surface, respectively. The developed method dies provide a state-of-art and effective method to the in-situ AOI, especially in 3-D full-field surface profilometry.

References