Solution for Shiny Specular 3D Mechanical Surface Measurement using Combined Phase Shift and Gray Code Light Projection

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Abstract

Non-contacts 3D shape measurement has been widely studied and applied to many advantages in terms of speed, accuracy and ease of implementation. However, the measuring system is still limited when measuring surfaces with high reflectivity by the optical signal cannot be obtained correctly. This paper proposes a new approach to solve the problem of measuring mechanical surface with high implementation. The appropriate exposure times in each region of the histogram are determined, then point clouds are merged at appropriate exposure times to obtain a good quality point cloud to avoid the saturation region on the CCD. Two different aluminum surfaces profile parts are measured with using single exposure time and proposed solution. Experimental results prove that the proposed solution can inspect the 3D surface of the mechanical parts with high surface reflectivity.

Keywords: *3D shape measurement, Fringe projection, Shiny surface, High dynamic range*.

1. Introduction

Currently, 3D measuring system with structured light being studied, developed and widely applied. In industry, this measurement method is applied to measure mechanical parts because of its advantages of full-filed inspection, high speed, high resolution and easily implemented. However, measurement system still had difficulty measuring the shiny objects or objects with a large range of reflectivity variation across the surface. Especially, the CNC machining parts have smooth and high specular surface.

Measurement method using fringe projection is optical measurement methods used to collect the image sensor and image processing information. 2D coordinates of the object are determined by measuring the coordinates of pixels on the image sensor. The depth of the object is determined through the phase differences of the pattern projected onto the surface measured against the original reference plane [1].

For mechanical high specular surfaces, the used fringe projection methods are quite difficult to capture high quality fringes. Because the light reflected by specular surface with large intensity leads to CCD camera being saturated. This effect changes the brightness values on the measured object and interference projection or even loss of surface information when collecting images with the camera. Thus, the image data would not be compatible with the original data and image data objects will be incorrectly.

Researchers have studied method is of reducing the influence of gloss surfaces such as:

(1) Techniques using multiple exposures [2] with a sequence of images captured at different exposures is combined into a single set of HDR (high dynamic range) image. Thus, the brightest unsaturated intensities at each pixel is selected. However, the signal to noise ratio (SNR) is small for low reflectivity regions, for the surface with a large range of reflectivity variation. Otherwise, the quality of measurement is hard to be ensured. Since the used exposure time is subjectively selected, it lacks quantitative manner to determine the proper exposures;

(2) Methods of adjusting projected light intensity [3] with an adjustable input gray. The intensity adjustment based on the camera's sensitivity and the reflectivity of the surface. However, during measurement of the object position measuring very hard to ensure features like the table of calibration so the coordinates after mapping matrix may be inaccurate;

(3) Methods using polarizing filters [4] may limit the reflected light incident on the CCD camera at a certain angle. However, the energy loss through the filter will reduce the captured intensity for the whole image, the resulting in SNR is low. Furthermore,

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when using polarizing filter will increase the complexity when building the system's hardware.

In this paper, a solution reduces the influence of the specular surface of measured objects using merged point clouds measuring at the appropriate exposures. The appropriate exposures in the Histogram is determined by the maximum percentage of pixels with the intensity levels of gray 50 ÷ 200. The method that allows a structured light system to successfully measure the 3D surface of objects with unknown reflective surfaces.

2. The principle of measurement

In this study, phase-shifting and Gray code algorithm is applied and developed to measure the mechanical surface objects correctly. Also, reflective principle is presented to identify the key factors that influence saturation on CCD images. The proposed method reduces their impact to system accuracy.

2.1 Principle of combined phase shift and Gray code

The principle of the measured method is based on the combined phase shift and Gray code method. The phase shifting fringe patterns with period T and Gray code patterns with 2^n subspaces are projected sequentially. Each subspace of Gray code corresponds to one period T of a phase shift fringe [5]. Each subspace is a unique Gray code value k_G. Theoretically, the wrapped phase Φ_w obtained by phase shift method. The absolute phase Φ_t may be determined through unwrapping phase by Gray code.

$$\Phi_t = 2\pi k_G + \Phi_w \tag{1}$$

The continuous phase Φ_t can be used to reconstruct the coordinates (x, y, z) base on the triangulation method. The obtained relative phase value depends on the intensity of the image. Typically, the light intensity of the image obtained in the camera shall not exceed the largest intensity value of the image sensor, for example 255 for 8-bit pixel depth. However, when measuring high-reflective surface, surface reflectivity has a large range. The intensity reflected from the surface to the CCD makes the pixels easy to reach or exceed the saturate value. If the reflection of light on the surface of the object with energy greater than the energy that the camera obtained (with gray level from 0 to 255), camera's image sensor will be saturated. Thus, phase values of saturated pixels cannot be calculated properly from fringe images. The surface profile information is not accuracy obtained.

2. 2 Principles of reflective surfaces

The surfaces measurement principle is reflective. Measurement objects with metal materials, optical uniformity and non-transparency, diffuse light through surface is very small and can be ignored. The reflected rays are determined entirely by the characteristics of light reflected from the surface. Thus, the reflected surface only has two components: reflected and scattered.

To solve the problem of saturation of the CCD, The relationship between the light intensity obtained by the camera $I_c(u, v)$ and the intensity of light from the projector $I_p(u, v)$ understanding of how image is received on the camera's CCD is determined. Factors affecting the formation of the pattern of image pixels reflecting surface R_A include: 1. Ambient light projects directly to the image sensor with intensity I_m; 2. Light encoded with projector intensity I_p from the projector and reflected from the point with surface reflectivity R_A is R_AI_p; 3. Ambient light I_m and the light from the surface portion other R_B to-point surface reflectivity R_A is R_A $(I_m + R_BI_p) = R_A$ $(I_m + I_B)$; 4. The exposure time of camera t; 5. The sensitivity of the camera ξ and 6. The camera sensor noise I_n [6].

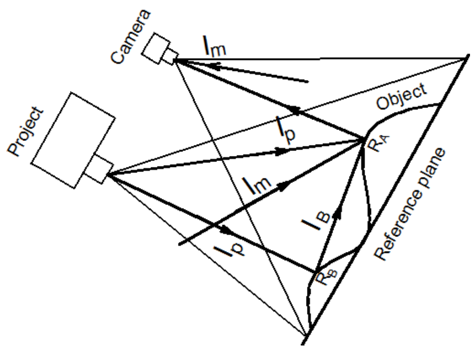


Fig. 1. Principle of surface reflection.

The pixels value $I_c(\mathrm{u,v})$ for the image points can be represented as:

$$I_c(\mathrm{u,v}) = \xi t R_A I_p(u,v) + \xi t[I_B(1+R_A) + I_m] + I_n \tag{4}$$

where, (u, v) are the coordinates of the pixels in the image plane.

2.3 Method of reducing the influence of the shiny surface

In the Eq. (4) to ensure fringe patterns obtained with good quality, the value of the parameters need to be set properly. Eq. (4) can be simplified into:

$$I_c(u,v) = t\xi R_A I_p(u,v) \tag{5}$$

According to the study [7] and [8], the appropriate exposure time can be achieved when $\xi R_A I_p(u,v)$ is determined:

$$\text{Set } \xi R_A I_p(\mathrm{u,v}) = \frac{I_0}{t_0} \tag{6}$$

replaced Eq. (8) by Eq. (7)

$$t^{su} = \frac{I_c^0(u,v)}{I_0} t_0 \quad (7)$$

Eq. (7) shows that each pixel corresponds to an appropriate exposure time t^{su} and it may be obtained when I_0 and t_0 be determined. An appropriate exposure time is only enough to provide exposure to a range of R_A small changes. Thus, in the entire region of the intensity variation of the surface can be divided into small areas, the exposure time of each small area is also easily identified.

Due to the reflectivity R_A of mechanical surface is an unknown input, which the surface reflectivity and the obtained intensity have a linear relationship. Thus, the change in surface reflectance can be determined by varying the intensity obtained from the CCD. The distribution of light intensity histogram of the CCD can determine in advance the nature of the surface reflectance and predict the appropriate exposure time for each specific measurement surface. A raw image of the object will be collected with reference intensity I_p (255) then use Histogram chart to determine the appropriate exposure times. The curve of Histogram chart has been smoothed and removed high frequency noise f_c by using low pass filter algorithm.

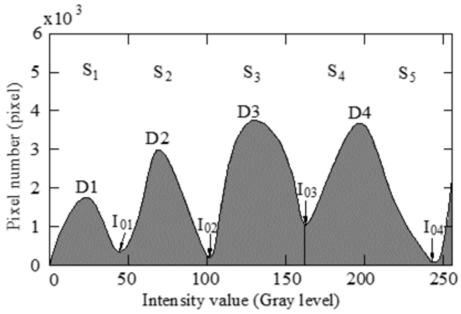


Fig. 2. Histogram of intensity

Histogram is a graph showing the number of pixels in an image at each different intensity value found in that image. As the chart in Fig.2 shows the intensity distribution for an 8-bit grayscale image. There are 256 Gray level of intensities. The values of regions S_i *(i=1, 2, 3, 4, 5)* is divided respectively S_1=0÷50; S_2=50÷100; S_3=100÷150; S_4=150÷200; S_5=200÷255. The number of vertical pixels correspond to the light intensity value of horizontally. The function $p(S_i)$ is a ratio of the total number gray level pixels I in region S^i by the following formula:

$$p(S_i) = \frac{n_I}{n} 100\% \quad (8)$$

With n_I is the number of pixels of magnitude in S_i, n is the total number of pixels in the image.

Histogram determines appropriate exposure times for any surface by considering areas S_1 and S_5. If the image has a small exposure time, the gray area will appear in the S_1 region and then $p(S_1)$ will be the largest. If the image has a large exposure time, gray level will appear in the S_5 area, meaning that $p(S_5)$ will be the largest. For surface with low reflectance, gray region will focus in the region S_1 and S_2, the value of $p(S_1) + p(S_2)$ will be greatest. If the surface has a high reflectivity, the gray region will focus in the S_4 or S_5 and $p(S_4)$ or (S_5) will be greatest.

Thus, a surface with high contrast and avoiding effect of surface reflectance and appropriate exposure times, the top of histogram focuses on S_2, S_3 and S_4, satisfies the following:

$$\sum p(S_{2,3,4}) = \big(p(S_2) + p(S_3) + p(S_4)\big) \to max \quad (9)$$

The appropriate exposure time is determined for each region or between regions, if the region does have variation greater intensity I_{cn} >1000 pixels (with peak intensities, *D1, D2, D3, D4, D5* in Fig.2). Appropriate exposure time of each region or between the two regions will be identified with an intensity corresponding to the bottom right of the top or bottom between two peaks in the two regions adjacent I_{0i} *(i=1, 2, 3, 4)*. Exposure time t_{0i} *(i=1, 2, 3, 4)* corresponding to each intensity is determined by the Eq. (7) of this time will be used to measure the code phase combinations Gray images synthetic intensity obtained.

3. Experiment result and discussion

The effectiveness of the proposed method with a specific experimental system is shown in Fig.3.

The experimental system includes: A digital camera (DFK 41BU02) with 1280 x 960 resolution, a video projector (InFocus N104) with 960 × 1280 pixels. To encode the reference plane using 4-step phase shifting with period T = 16 pixels, combined with the length 6 Gray code bits corresponding to each period T is a Gray code. By adjusting the focal plane of the camera and projector until overlap, the whole volume is achieved 250x180 mm in projection distance L = 500 mm and the distance from the projector to the camera is determined b = 130 mm. The camera has exposure time range t = 1/200 s ÷1/4 s = 5 ms ÷ 250 ms.

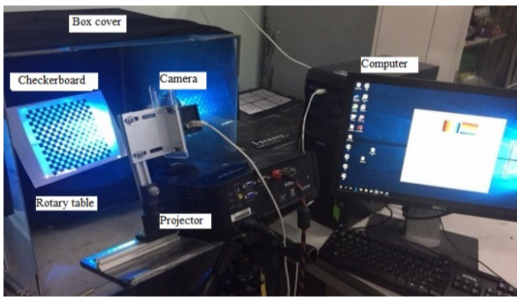


Fig. 3. Setup the experimental system

3.1 Experimental determination of the linearity of the measurement system

The gray scale response of projector is tested to ensure the accuracy of system measurement.

The first experiment, the gray level is changed from 0 to 256 levels and measures an aluminum workpiece on the surface. During the experiments, the ambient light is kept constants and the temperature surround is 25^0c.

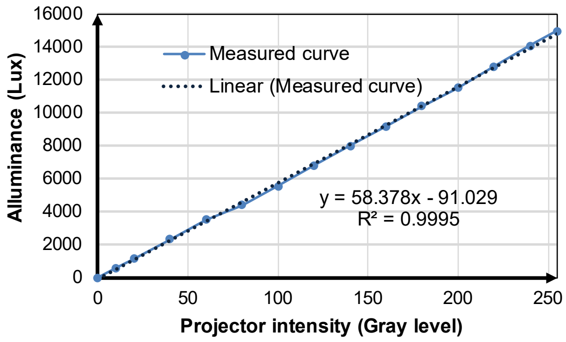


Fig. 4. Graph of the relation between projector and illuminance

The Fig.4 shows result of the first experiment; the projector intensity and illumination have a good linear relationship. This indicates that the projector's response is linear.

The second experiment, camera exposure time is changed from 5 ms to 250 ms and the captured intensity is obtained at each different exposure time value. According to Fig. 5, the result of the second experiment, the camera exposure time and captured intensity are linear relationship. This indicates camera's response is linear.

It is possible to use a Histogram of intensity *I* to determine the appropriate exposure time. The exposure time can be used to represent the intensity *I* or for each specific surface.

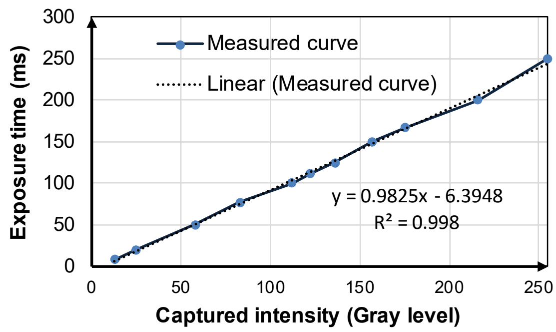


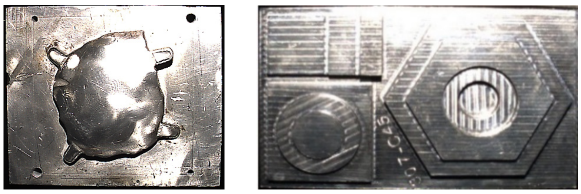
Fig. 5. Graph of the between captured intensity and exposure time

The surface reflectivity R_A is an unknown input value. The captured intensity is linear. Thus, the change in reflectance of surface could determine through the change in captured intensity from the camera CCD.

In this experiment, in order to obtained lower reflection of surface, camera exposure time must be selected in the small range.

3.2 *Experimental reducing the influence of the shiny surface*

Aluminum is one of the materials with a surface reflection coefficient of almost *1*. It is higher than steel, which is also common using in processing CNC machining. So that the experiment evaluated effects of the solution was executed on two workpiece of aluminum parts. One aluminum mount has complex profile and the other an aluminum part has step height profile.



a, b,

Fig. 6. Image of aluminum mount (a)
Image of height step aluminum part (b)

In the first experiment with an aluminum mount in Fig.6 (a). The Gray code 2^0 with light intensity I_p (255) is projected by the projector mapping onto object. The images are further obtained by the camera with different preliminary exposure times t_{sb}. The t_{sb} is selected in the range of camera exposure times: 50 ms, 25 ms, 16 ms, 12,5 ms, 10 ms.

The histogram is constructed with each exposure time and calculates the $\sum p(S^{2,3,4})$ according to equation (9).

Table 1: Preliminary exposure time table

Exposure time	t_{sb}(ms)				
	50	25	16	12.5	10
$\sum p(S_{2,3,4})$	10.66	29.52	71.26	56.29	19.45

In table 1 with exposure time t_c=*16* ms, the value $\sum p(S_{2,3,4})$ is the largest value. So t_c=*16* ms is selected as initial exposure time for calculated histogram of I_0.

Experimental measurements with measurement methods are proposed in section 2.3. First, projecting the raw intensity of light I_p=*255* with exposure time originally set $t_0=16$ ms collection of photos and use the histogram to compute the intensity respectively.

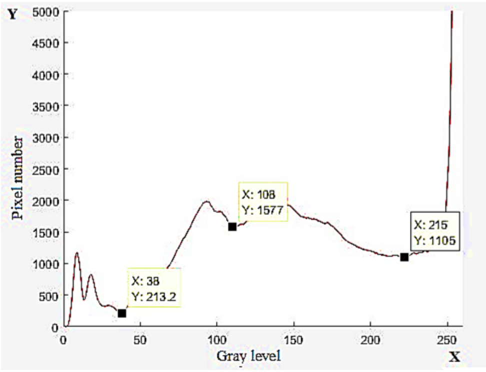
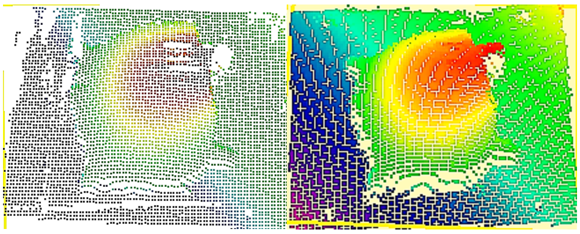


Fig. 7. Calculate intensity I_{0i} of aluminum mount

In Fig. 7, the I_{0i} determined is shown on screen with illumination $I_{01}=38$, $I_{02}=108$, $I_{03}=215$, the intensity is used to calculate the exposures corresponding to $t_0=16$ ms, $I_c^0 = 254$ according to formula (7) $t_{01}=106.94$ ms, $t_{02}=37.62$ ms, $t_{03}=18.90$ ms. The exposures will be used to measure by the phase shift method combines Gray code. Then merged at three exposures point cloud reconstruction.



a, b,

Fig. 8. 3D point cloud of an aluminum mount in single exposure (a), in merged point clouds at 3 appropriate exposures (b),

The reconstructed 3D results after single exposure $t_0=16$ ms show in Fig. 8(a) with 6062 points. The point cloud has large areas of holes due to the saturation. The point cloud obtained after merger the point cloud with 3 appropriate exposure times shows that the pixels show a very thick surface. The total number of pixels representing the 3D surface is 13135 points.

In the second experiment, an aluminum part with step height (Fig. 9). The Gray code the pattern 2^0 with light intensity I_p (255) is projected by the projector onto objects. Then images are obtained by the camera with different exposure time t_c: 50 ms, 25 ms, 16 ms, 12,5 ms, 10 ms.

The histogram is constructed with each exposure time and calculates the $\sum p(S_{2,3,4})$ arcoding to equation (9).

Table 2. Preliminary exposure time calculated table

Exposure time	t_c(ms)				
	50	25	12.5	10	5
$\sum p(S_{2,3,4})$	9.35	39.8	69.71	65.96	39.32

In table 2 with exposure time $t_c=12.5$ ms, the value $\sum p(S_{2,3,4})$ is largest. So $t_c=12.5$ ms is selected is initial exposure time for calculated histogram of I_0.

Experimental measurements with measurement methods are proposed. First, projecting the raw intensity of light $I_p=255$ with exposure time originally set $t_0=12.5$ ms collection of photos and use the histogram to compute the intensity respectively.

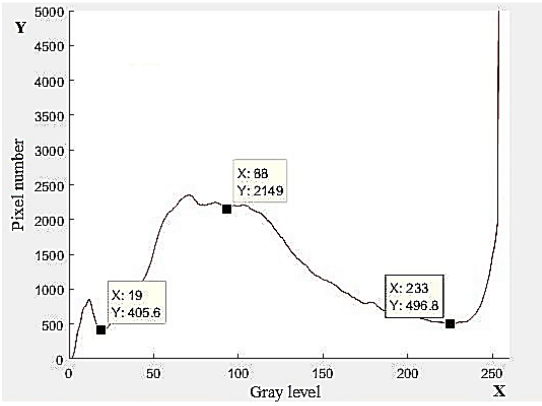
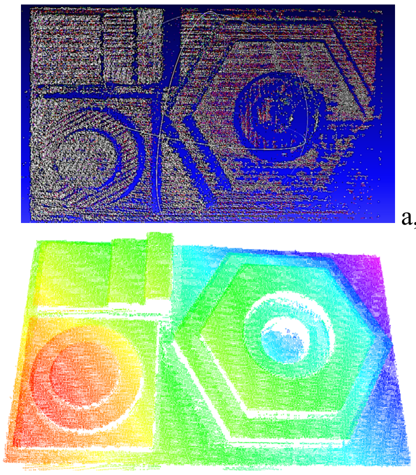


Fig. 9. Calculate I_{0i} intensity aluminum part



a,

b,

Fig. 10. 3D point cloud of an aluminum part in single exposure (a), in merged point clouds at 3 appropriate exposures (b),

In Fig.9, the I_{0i} determined is shown on screen with aluminums $I_{01}=19$, $I_{02}=88$, $I_{03}=233$, the intensity is used to calculate the exposure time corresponding to $t_0=12.5$ ms, $I_c^0 = 254$ according to formula (7) t_{01}=167.1 ms, t_{02}=36.07 ms, t_{03}=13.62 ms. The exposure time will be used to measure the phase shift combined with Gray code method. Then summing the intensity image and absolute phase map and point cloud reconstruction Fig.10.

Aluminums part is measurements with single exposure time is set $t_0 = 12.5$ ms obtained a 3D point cloud of aluminums as shown in Fig. 10 (a). The total number of pixels reconstructed point cloud are 23928 points. The point cloud of part missing information due to the pixels on the CCD is saturated not get the signal, so the surface will not be built. The point cloud obtained after merger the point cloud with 3 appropriate exposure times shows that the pixels show a very thick surface. The total number of pixels representing the 3D surface in Fig.10 (b) is 87719 and the number of pixels after using the *Downsampcloud* algorithm is 29419 pixels.

4. Conclusion

In this paper, the method that allows a structured light system to successfully measure the 3D surface of objects with high range of surface reflectivity without knowing the property and scene geometry. Through the histogram of the raw image, the measurement part can determine how much exposure time is appropriate for the image to have the full range of grayscale from 0 ÷255 gray scale. The point cloud is obtained in merged point clouds with a sharp surface and no loss of information.

The surface of the components is different in shape, the surface reflectivity is different. Experiment results show that the surface have high reflection should chose small the exposure time. The result presented demonstrate efficiency of proposed technique for inspection full-field reflectance surfaces without auxiliary equipment.

Acknowledgments

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