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Optimal Parameters Selection for 3D-Mechanical Surface Measuring Equipment Based on the Structured Light Gray Code

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Abstract

3D reconstruction techniques of object by using the structured light are widely used in the industry and academia. This method gives some advantages like fast and accurate. The measurement precision of a certain system depends on the geometrical parameters of the system, the characteristics of the surface under test and the specification of devices. In this paper, the effect of some parameters on the resolution of the 3D surface measurement equipment based on Gray code technique, especially the position correlation between the camera and the projector is investigated. Thereby, the paper proposes the selection of optimum parameters for the measurement system. Experimental results determine the optimum conditions for the system at the measuring range (w x h = 400 mm x 300 mm) to obtain the best z-resolution of 0.67 mm.

Keyword: 3D measuring devices, coded patterns, structured light, computer vision.

1. Introduction

3D Surface Optical Measurement is the process of digitizing a surface object using optical sensors. With the computer science improvement, the measurement became easier and faster. In recent decades, the structured light method has been extensively studied and has been applied in many fields of modern technologies such as precision manufacturing, health sciences, security, and entertainment [1].

Typically, the measurement system using the structured light consists of: a single camera and a single projector that projects a light pattern on the measuring surface. The light pattern is encoded by the intensity function. The depth information can be extracted by measuring distortion between the captured and the reflected image. The target object should remain stable during the scanning process. The object 3D position can be obtained by triangulation method.

The binary code or Gray code method has been created using some techniques such as analog fringe generation methods (e.g. Grating) [2, 3] and binary image coding with a projector [4, 5]. Two binary coding methods have advantages of simple optical arrangement, simple computation and robustness. Moreover, comparing to grating projection methods, the digital fringe projection methods tend to be more flexible, easier, and faster [6].

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The binary coding method was first proposed by Posdamer and Altschuler [7] in the field of a formulation with sequential projection of *n* samples to encode into 2^n still using binary coding. Each pattern on the final template has a unique binary code. In these techniques, only two illumination levels are commonly used, which are coded as 0 and 1. The symbol 0 corresponds to black intensity while 1 corresponds to full illuminate white. However, the pixels on the same strip have the same binary code, so that, to obtain coordinates of the measurement points it is necessary to determine the center of the fringes or boundary of the fringes on the object when conducting the triangulation algorithm. The advantages of Gray code is that consecutive code words have a Hamming distance of one, being more robust against noise [8].

The maximum number of patterns that can be projected is the resolution in pixels of the projector device. To get a better resolution, a larger number of patterns is needed. However, reaching this value is not recommended because the camera cannot always detect such narrow stripes [9].

The structured light that is used in this paper is Gray coding with projection patterns with only alternating white and black stripes. This paper presents a method for determining the optimum parameters of the 3D measuring system using structured light in order to minimize z_{min} resolution and compact design.

2. Measurement principle

Figure 1 shows the principle of a structured light measuring system using sequential Gray coded patterns project on the measured object and a camera captures images pattern on the object.

The measurement process is controlled by a computer: The computer connected to the projector controls the sequential patterns of image that are encoded onto the measuring object. The computer processes the images obtained from the camera. A software is programed to project the structured light of texture structure of the projector, to control the movement of part under test, to acquit 3D images, and to reconstruct 3D profile of the measuring object.

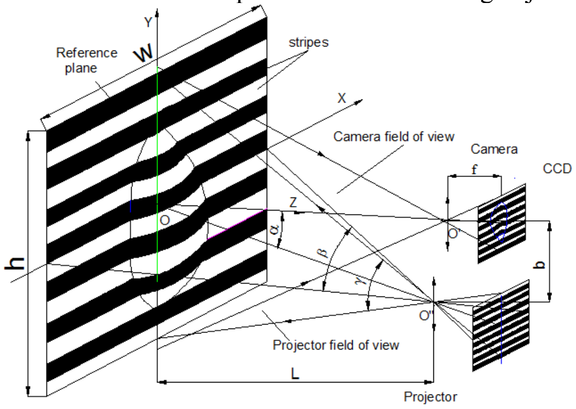


Fig. 1. Schematic diagram of measurement system.

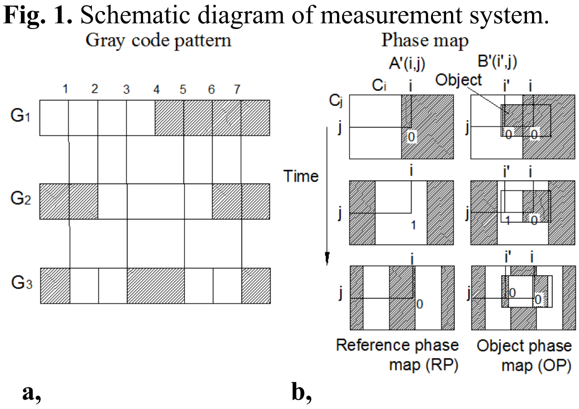


Fig. 2. Find tripe egged in Gray code pattern (a) and phase map on CCD camera (b)

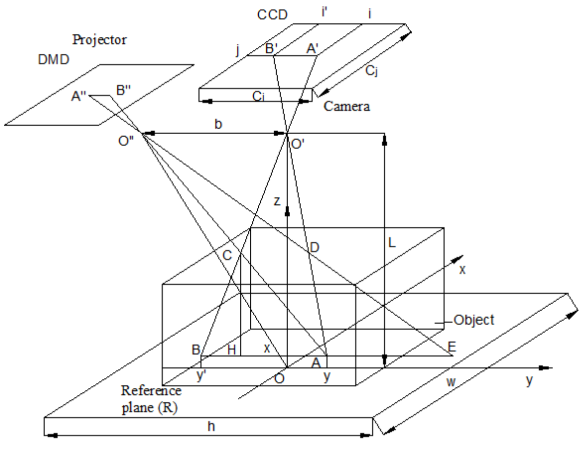


Fig. 3. Optical Geometry of the measuring system [3]

In order to remove one-bit decoding error of Gray code based on pixel center, to increase the accuracy of image sampling point location, and to keep the correspondence between image sampling point and object sampling point, encoding and decoding method based on stripe edge of Gray code is presented.

Due to the influence of ambient light and the reflection of measured surfaces, the white and black stripes in the image can change over different regions of the image. The structured light Gray code method projects both normal and inverse stripe patterns, to prevent the effects of lighting conditions. Then by finding the intersection of the two normal and inverse image, the stripe edge is located.

When 3D reconstruction, the Gray level image with projector effects to quality image captures by the camera. Therefore, the field of appropriate illuminance can be determined for best quality image and high resolution.

As shown in figure 2, for example, three Gray code patterns are projected, and there generate 2^3-1 edges. The reference plane is divided into 8 sections that is stripes, which have a certain width and projection sequence with a unique intensity code and is represented by a code word. Sample images are shown in the order of G1, G2, and G3, the first stripe intensity from left is white, white, and white so the corresponding code word is 111.

The measuring system is constructed with several extrinsic parameters defined as the field of view ($w \times h$) of the device which is the space that can be seen both from the projector and the camera. This area depends mainly on the parameters of the system such as: the distance between the camera and the projector b, the angle between the camera axis and the projector axis α, the distance between the center of the camera and the projector to the reference plane (R) L.

Each pixel on the camera's CCD is determined by the value of row i and column j. The size of the camera CCD is $C_i \times C_j$ called the image plane.

The algorithm determines the 3D coordinates of the object based on the triangulation method. The coordinates of a point on the reference plane are determined by the point on the image plane by two parameters: the pixel coordinates and the code word obtained by displaying sequential patterns project on the plane R.

When Gray light is projected on the plane R, the phase map of the projection plane (RP) is mapped. When the object is placed on an (R) plane, an object presents a parallel-epipedic shape. The phase map is mapped to an object (OP). The height of the object is determined by the phase difference between the pixel on the phase map RP and the phase map OP.

As shown in Figure 3, point A lies on the plane R. When there is no object, point A is seen at pixel A' (i, j) on the CCD and has the code word of point B'' on the projector's DMD.

As an example in Figure 2, in case $n = 3$, the code word of point A stores the bit of pixel B' sequence (0 1 0). When an object is placed on the plane R, ray O''A intersects the object at point $C(x, y)$ which is seen at pixel A'(i, j) on the CCD. This is the direction of ray O''E, which strikes the object at point D. The point D on the image maps to pixel B'(i', j) on the CCD.

Evaluation of the height $z(x, y)$ of point C on the object is the distance $\overline{CH}$. The distance $\overline{A'B'}$ is determined. In the case, the stripes are parallel to the x coordinate, the distance $\overline{A'B'} = \Delta i = i - i'$. The distance $\overline{AB} = \Delta y = y - y'$ on plane R is determined by the formula [3]:

$$\overline{\mathrm{AB}} = \Delta \mathrm{y} = \Delta \mathrm{i}.\frac{\mathrm{h}}{C_i} \quad (1)$$

Where: C_i is the vertical height of the CCD sensor.

The two triangles ACB and O'CO'' are similar and that the following relationship holds:

$$\frac{\overline{\mathrm{AB}}}{\overline{\mathrm{O'O''}}} = \frac{\overline{\mathrm{CH}}}{L - \overline{\mathrm{CH}}} \quad (2)$$

Where $\overline{\mathrm{CH}} = z(x, y)$, $\overline{\mathrm{O'O''}} = b$

$$\mathrm{z(x,y)} = \frac{\mathrm{L}.\Delta \mathrm{y}}{\Delta y + b} \quad (3)$$

Because the projected stripes are parallel to the X direction, pixels that have the same Y coordinate present the same Gray-code word. Thus the resolution along the X coordinate depends on only the resolution of the CCD matrix. Below we consider the dependence of the resolution on the Y coordinate. The minimum measurable value of $z\ (x, y) = z_{min}$, is expressed by

$$\mathrm{z}_{\min} = \frac{\mathrm{L}.\Delta \mathrm{y}_{\min}}{\Delta y_{\min} + b} \quad (4)$$

According to the formula 4, the resolution is defined as the minimum distance $\overline{AB}$ is $\overline{AB} = \Delta y_{\min}$. Then the distance $\overline{A'B'}$ is the smallest from Eq (1), where $\overline{A'B'} = \Delta i_{\min} = 1$ (A' and B' are two adjacent pixels). According to formula (3) at this time

$$\Delta y_{min} = \frac{h}{C_i}$$

$$\mathrm{z}_{\min} = \frac{\mathrm{L}.\frac{\mathrm{h}}{c_i}}{\frac{\mathrm{h}}{c_i} + b} \quad (5)$$

From formula (5), the z-resolution can be increased by decreasing L, h and increasing b. Parameters L and h are interdependent depending on the optical properties of the camera.

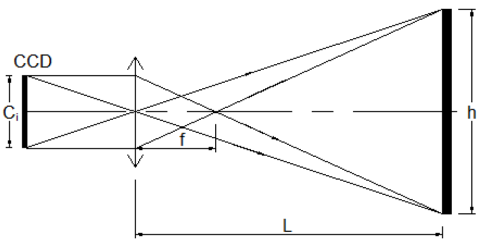


Fig. 4. Image lens of camera

Normally, the vertical projection area is smaller than the horizontal dimension ($h < w$) so that, the short image direction h is selected. The value h is large enough to observe the whole object and small enough to optimize the measurement resolution.

As shown in Figure 4, the relation of the projection height h and the height of the CCD sensor through the distance L and the focal length of the camera lens f are determined by the formula [10].

$$\frac{h}{C_i} = \frac{L - f}{f} \quad (6)$$

Substituting formula (6) into (5) we have:

$$\mathrm{z}_{\min} = \frac{L(L - f)}{bf + L - f} = \quad (7)$$

Eq. (7) suggests that measurement resolution can be increased by reducing the parameter L or increasing the parameter f. However, if h is constant, the ratio L/f should be constant. Therefore, we need to calculate L and f accordingly. Finally, Eq. (7) is used to determine the value of parameter b, which optimizes the measurement resolution. A noteworthy is that care must be taken in choosing the value of b. However, if the larger the projection angle of the projector to the large reference plane, the greater the width and the greater the deformation of the projections, the higher the resolution.

3. Experiments and discussion

The system composes of a DLP projector (InFocus N104) working at 1024 × 768 pixels. A camera (DFK 41BU02) with 1280 × 960 resolution. A standard PC was used for implementing the algorithms.

As illustrated in figure 5, the whole experimental system based on the geometric constraint. The rotary table is designed to be rotatable so that the scanning area on the object is maximized, with the main movement rotating on the plane R.

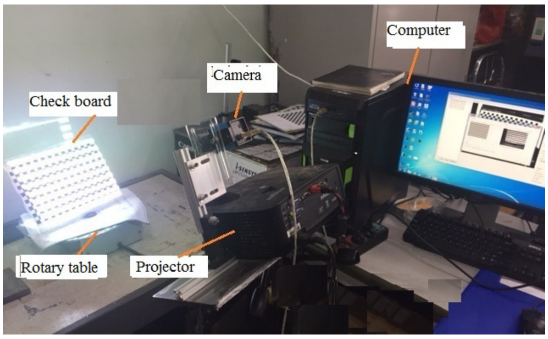


Fig. 5: Experimental system.

The experiment was carried out to select value of illumination for high resolution. The Gray - level of the program creating a binary pattern was changed from 10 to 255 levels and measure the illuminance pattern on the reference plane. During the experiment the ambient light had an average illuminance of 18 (lux) and an average ambient temperature of 25 °C.

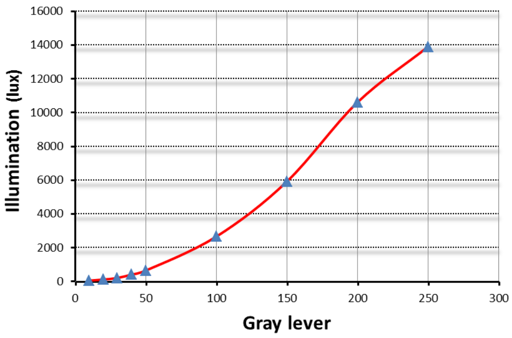


Fig. 6. Graph of relationship between illumination and Gray- level

According to the figure 6 when projecting patterns at low illumination intensities, the signal to noise ratio of the system decreases and, therefore, the depth from low reflective regions cannot be obtained. On the other hand, when projecting high illumination intensity patterns, depth from regions with high reflectance cannot be recovered due to pixel saturation. Therefore, Gray-level values are selected in area of 100 to 200.

For determining the projection screen of the projector: Use off-axis projection and projection horizontally and vertically as symmetry. The angles projection horizontal and vertical γ and β are shown in Fig. 1. Because the projector has a zoom lens, there are a variety of offset ratios. To project the clear projection on the reference plane, it is necessary to change the projector focus to a certain distance. So choosing the scaling factor of projection to experiment the relationship between projection distance and projection width is necessary.

Experiment to change the distance L and adjust the projector's focus so that the image is clear on the plane R to determine the horizontal and vertical projection area $w \times h$. Thereby, the relationship between the distance L and the vertical projection area h is calculated.

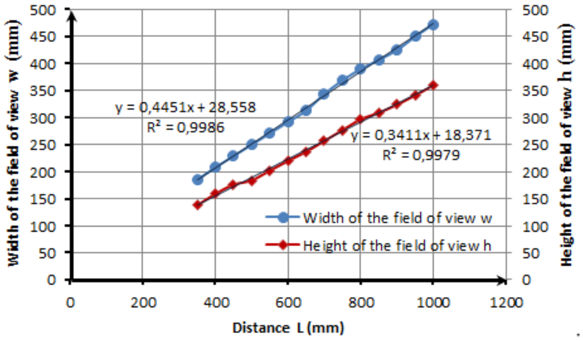


Fig. 7. Graph of relationship between L , w and h

The relationship between the distance L and the viewing area $w \times h$ when the offset ratio is 100%. The data was processed and graphs were drawn using MS Excel 2010.

According to figure 7, the relationship between L, w and h has a correlation coefficient R^2 = 0.9986 and R^2 = 0.9979, respectively, which is relatively linear. Therefore, it is possible to determine half-angle in two directions.

Half projection angle horizontally and vertically can be calculated according to the following formula:

$$\frac{\beta}{2} = arctg\left(\frac{w}{2L}\right) \Rightarrow \frac{\overline{\beta}}{2} \approx 13{,}8^0$$

$$\frac{\gamma}{2} = arctg\left(\frac{h}{2L}\right) \Rightarrow \frac{\overline{\gamma}}{2} \approx 10{,}3^0$$

Based on the determination of the angle β it is possible to determine the distance L so that the vertical projection area is $h = 300$ (mm).

$$L = \frac{h}{2tg\frac{\overline{\gamma}}{2}} = \frac{300}{2tg\left(10{,}3^0\right)}$$

$$L \approx 820(mm)$$

Given L = 820 (mm) horizontal projection area can calculate by:

$$w = 2L\tan\left(\frac{\beta}{2}\right) = 2.820\tan\left(13{,}8^0\right)$$

$$\Rightarrow w = 400(mm)$$

For the experimental system using a camera resolution (1280 × 960) and the actual pixel size of 4.65 (µm), it is possible to calculate and select the size of the lens so that the recording area the camera covers the projection area of the projector on a standard plane.

The actual size of the camera CCD in horizontal and vertical directions:

C_i = 1280 x 4,65.10^{-3} = 5,952 mm

C_j = 960 x 4,65.10^{-3} = 4,464mm

From Figure 4 we have the focal length of the camera lens to achieve the smallest image area of h = 300 (mm) and L = 820 (mm).

$$\Rightarrow f = \frac{LC_i}{C_i + h} = \frac{820.4{,}464}{4{,}464 + 300} = 12{,}01(mm)$$

The shortest focal length f = 12 (mm) for design optimization is used.

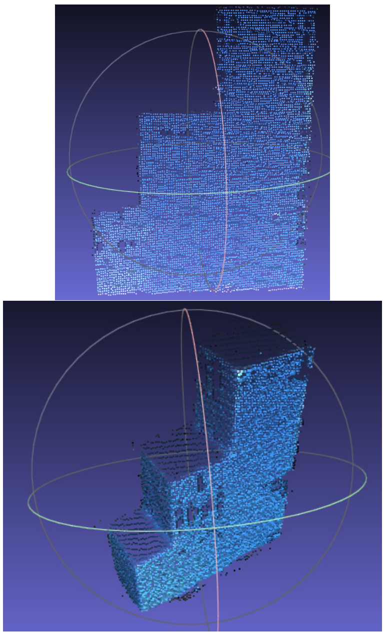


Fig. 8. 3D point clouds of height step object

With the distance L and the focal length of the camera f identify above, experimentally changes the distance b, to determine the relationship between b and the resolution of the equipment. The distance between the camera and the projector will be changed from as close as possible to as far as possible; each time a standard tiered metering is performed.

With b values varying from 80 to 200 mm, measurements and cloud point measurements are made. From the 3D point cloud data, the distance between the pixels in *x, y, z* directions determine the resolution. An average value of resolution in different directions is obtained by the distance measurements that were carried out 25 times. 3D point clouds have been processed and measured resolution on Geomagic 2012 software

The relationship between average resolution *(x, y, z*) and distance b is shown in Figure 8. The average resolution in *x* and *y* axis does not change much when b changes. Thus, the resolution of the *x* and *y* directions does not depend on the change of the distance between the camera and the projector.

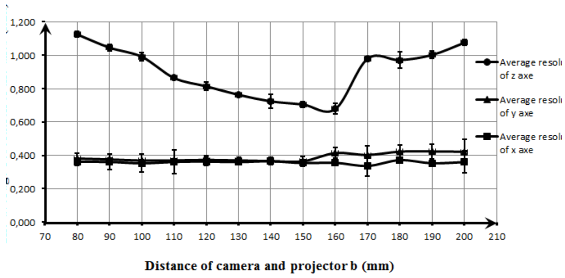


Fig. 9. Graph of relationship between average resolution of the axes and distance b

However, the average resolution of the z axis varies considerably when the distance between the camera and the projector varies. On the graph we see with increasing parameter b from 80mm to 160mm, the z resolution has been reduced from 1,12 mm to 0,67 mm. The parameter b from 160 to 170 mm the system have some errors so the z resolution increasing suddenlly. The reason for that the angle between projector and reference plane has been too large. Which make larger the stripe than allowable value. Therefore, the system can't compensate error and return real value. With parameter b = 160mm, the z resolution reachs in minimum of 0.67 mm. From experimentally determined with b = 160 mm, the z resolution is the best resolution.

On the graph we see that the standard deviation of the resolution in axes is quite small.

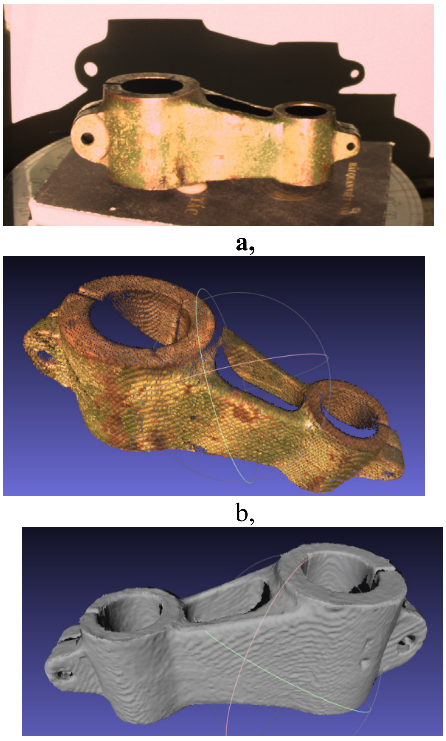
From calculation and identification of binary code structured light measurement system, the paper proposes the process of optimizing some parameters of the system to obtain the best z-resolution as follow:

1. Investigate the projector to determine the measuring area and the distance from the projector to the calibrated screen to suit the requirements.

2. For symmetric projectors, the half-angle projection from which the minimum projection width is fixed to the fixed distance L.

3. Through the projection area size, select the appropriate focal length of the camera lens to obtain the whole projection area.

4. Determine the optimum distance between the camera and the projector to achieve optimum projection and compact design



a,

b,

c,

Fig. 10. Reconstruction 3D map result
a, Image of measurement
b, Point cloud reconstruction
c, Point cloud registration

4. Conclusion

The calculation and determination the parameters of the system to reconstruct the 3D surface with good quality z resolution is presented. From the experimental results, the optimal parameters L = 820 mm, f = 12 mm and b = 160 mm can be determined at the maximum measuring range 400mm x 300 mm^2. The device can reconstruct the 3D surface of the object as shown in Figure 10 with the optimal resolution of z = 0.67 mm.

In this paper, the dependence of the height resolution on the parameters involved in the measurement has been studied. It has been shown how the resolution requirement determines the relationship between the camera and the projector. The experimental results prove that with the calculation and selection of the parameters of the system can be obtained resolution z in the best way, consistent with the theory.

Acknowledgment

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References

[1] J. Salvi, J. Pagâ, and J. Batlle, "Pattern codification strategies in structured light systems," Pattern Recognit., vol. 37, pp. 827–849, 2004.

[2] Q. Zhang, X. Su, L. Xiang, and X. Sun, "3-D shape measurement based on complementary Gray-code light," Opt. Lasers Eng., vol. 50, no. 4, pp. 574–579, 2012.

[3] G. Sansoni, S. Corini, S. Lazzari, R. Rodella, and F. Docchio, "Three-dimensional imaging based on Gray-code light projection: characterization of the measuring algorithm and development of a measuring system for industrial applications.," Appl. Opt., vol. 36, no. 19, pp. 463–472, 1997.

[4] T. Peng and S. K. Gupta, "Algorithms and models for 3D shape measurement using digital fringe projection," Mech. Eng., p. 249, 2006.

[5] H. B. Wu, Y. Chen, M. Y. Wu, C. R. Guan, and X. Y. Yu, "3D Measurement Technology by Structured Light Using Stripe-Edge-Based Gray Code," J. Phys. Conf. Ser., vol. 48, pp. 537–541, 2006.

[6] J. Batlle, E. Mouaddib, and J. Salvi, "Recent progress in coded structured light as a technique to solve the correspondence problem: A Survey," Pattern Recognition, Vol. 31, No. 7, pp. 963 - 982, 1998.

[7] J. L. Posdamer and M. D. Altschuler, "Surface measurement by space-encoded projected beam systems," Comput. Graph. Image Process., vol. 18, no. 1, pp. 1–17, 1982.

[8] Gupta, Pratibha, "Gray Code Composite Pattern Structured Light Illumination," Univ. Kentucky Master's Theses, p. 438, 2007.

[9] S. Rusinkiewicz, O. H.- Holt, and M. Levoy, "Real-time 3D model acquisition," SIGGRAPH '02 Proc. 29th Annu. Conf. Comput. Graph. Interact. Tech., vol. 21, no. 3, pp. 438–446, 2002.

[10] S. Zhang, High-Speed 3D Imaging with Digital Fringe Projection Techniques, Optical Sciences and Applications of Light, vol. 1. pp. 1-198 Published by CRC Press, 2016.