Accuracy and Stability for Optimum Performance of Digital Fringe Profilometry Method

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Abstract. Various method was developed for the acquisition of the three-dimensional surface of an object. One of the more popular methods used is the structured light profilometry method. It can capture a high-resolution three-dimensional object in real-time. Not only that, but this method is also non-invasive, which is very suitable for the measurement of fragile samples. This paper discusses the accuracy and stability of a structured light profilometry method that is used to obtain a 3D measurement. The experiment is done by using a calibrated camera and projector. A light pattern is then projected onto the sample and captured by the camera. The accuracy of the system is investigated by capturing a flat plate with an increment of 50 µm from 0 µm to 1000 µm. The result has shown a maximum percentage error of this system is 15.76% which is 9.3511 µm, and the minimum percentage error is 0.15% which is 0.7339 µm. For the stability test, the plate was captured thirty times at the same location, and the data obtained shows the consistency of the system has a minimum and maximum standard deviation of 2.4991 µm and 6.8886 µm, which is within 7 µm. The test on the feeler gauge shows a maximum percentage error of 2.12% which is 2.1671 µm.

1. Introduction

Computer vision has become an essential application in various fields, such as the medical field, industry and even for personal interest [1]. The manufacturer has widely used it for computer vision inspection of the manufactured product [2]. The inspection of products is critical as it is to ensure the quality of the product meets the required standard and avoid selling a low-quality product which may affect the company’s reputation. The inspection of the product is usually done by human labour, where it is time-consuming, and the accuracy depends on the fatigue level of the worker [2]. Besides, the work time of the human is lesser compared to machines [3]. Numerous industries have benefited from this application because it improves productivity and quality management and provides a competitive advantage to industries that employ this technology [3]. Besides that, computer vision also provides a non-contact three-dimensional (3D) inspection which is undesirable for the measurement of the soft or deformable objects [4]. Hence, high speed and high accuracy become a concern in computer vision [5].

Currently, there is a great deal of optical strategies and vision systems that have been developed, which is the optical 3D imaging using a structured light technique [6]. Mainly, there are four categories of 3D imaging method, which is laser scanning, time-of-flight, stereo vision and structured light [7]. Out of these four methods, the structured light 3D scanners have attracted much attention for
decades and have been extensively researched [5, 6]. This method mainly uses a setup consisting of a projector and camera, where the projector will project a pattern and is captured by the camera [9]. The depth of the object from the acquired can then be computed into 3D information through the triangulation calculation [10]. The advantages of using a structured light 3D scanning method are the high accuracy of measurement, high speed, low cost and easy configuration for hardware [4]. The structured light 3D scanning method is also referred to as fringe projection profilometry (FPP). The sinusoidal pattern used for FPP provides 3D information with high spatial resolution and high depth accuracy [4]. For the FPP, it can measure complex structures with a higher speed as it can scan a large area at a time compared to a laser scanning system [6]. Not only that, but FPP is also advantageous due to its pixel by pixel measurement, low sensitivity toward surface reflectivity variations, and low sensitivity toward ambient light [11]. A three-step phase-shifting algorithm is commonly used when high speed is required in FPP [11]. It also requires the minimum data needed to calculate the 3D information.

This paper presents an analysis of the accuracy and stability of shape measurement method using a camera with a Scheimpflug adjustment lens, LCD projector, and 3-step phase shifting. By using the phase-shifting technique, the 3D information of the object can be obtained. This paper discusses about the accuracy performance of scanning sample parameters. An experimental set up will be analysed and presented in this paper.

2. Methodology

2.1. Equipment and Software

In this study, the Basler axA2040-55uc USB 3.0 with Sony IMX265 Complementary Metal-Oxide-Semiconductor (CMOS) sensor is used as the camera and the lens installed into it is TCSM024: 3D bi-telescopic lens. This left comes with the Scheimpflug adjustment function. The software used to control the camera is pylonViewer, which can view and capture the image. A digital light projection (DLP) is used as the projector and is controlled by using LightCrafter 4500 software. The software can be used to flash the projector’s memory and control the projector. MATLAB is used to process the image captured. Figure 1 shows the setup for the experiment.

2.2. Experiment flow

The overall flow of the experiment is shown in Figure 2. The first step is to generate the fringe for 3-D data acquisition. Then calibration is done to obtain a high-accuracy 3D imaging. After the parameters are found, it will be used to calculate the sample’s 3D information.
Figure 2. The overall flow of the experiment

2.3. Fringe generation
In this experiment, three-step phase-shifting profilometry (3PSP) is used. 3PSP need three images of fringe pattern with phase-shift at -120°, 0° and 120° to obtain the 3-D data [12]. The fringe pattern is generated using Equation (1), (2), and (3),

\[ I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) - \alpha] \]  
\[ I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)] \]  
\[ I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \alpha] \]  

where, \( I_1, I_2, \) and \( I_3 \) are a fringe pattern with phase-shift at -120°, 0°, and 120°. \( I' \) is the mean intensity, \( I'' \) is the peak-to-valley intensity modulation, \( \phi(x,y) \) is the wavefront phase, and \( \alpha \) is 120°.

Two sets of fringes are generated as shown in Figure 3. The fringes are set to contain fringe with 6-pixel width and 120-pixel width fringe [12]. The fringe pattern is adjusted to have a phase-shift of -120°, 0° and 120°. The overall flow of fringe generation is as shown in Figure 3.

2.4. Calibration
The calibration of the 3D scanning system is summarised in Figure 4. The fringe is first projected, and then the image is captured by the camera at two known heights, 3 mm and 0 mm. For the 6-pixel width image captured, Gaussian Blur filter will be applied [13], whereas, for the 120-pixel width image captured, Gaussian Blur filter and Median Blur filter will be used. The filters are used to reduce the dense point artifact [14]. After that, the phase value, \( \phi(x,y) \), of each pixel will be calculated. The phase value, \( \phi(x,y) \), can be calculated by simultaneously solving Equation (1), (2), and (3) to obtain Equation (4).

\[ \phi(x,y) = \tan^{-1}\left(\frac{1-\cos\alpha}{\sin\alpha}\frac{I_1(x,y) - I_3(x,y)}{2I_2(x,y) - I_1(x,y) - I_3(x,y)}\right) \]  

After the phase for both the 6-pixel width and 120-pixel width fringe is obtained, the 120-pixel width fringe is used to unwrap the 6-pixel width fringe. This process is done by applying Equation (5).

\[ \phi_{uw}(x,y) = \phi_1(x,y) + 2\pi \cdot \text{Round}\left(\frac{\frac{T_1}{T_2}\phi_1(x,y) - \phi(x,y)}{2\pi}\right) \]
where, $\phi_{uw}(x,y)$ is the unwrapped phase, $\phi_1(x,y)$ is the 6-pixel width fringe, $\phi_2(x,y)$ is the 120-pixel width fringe, $T_1$ is the fringe size of pixel width of $\phi_1(x,y)$ and $T_2$ is the fringe size of pixel width of $\phi_2(x,y)$.

**Figure 3.** Fringe generation for three-step phase-shifting profilometry

Phase checking, $\gamma(x,y)$, is done to ensure that the quality of fringe capture is good, where there it has a high modulation index. It is calculated using Equation (6).

$$
\gamma(x,y) = \sqrt{\left(1 - \cos\alpha\right) \left(I_1(x,y) - I_3(x,y)\right)^2 + \left[\sin\alpha \left(2I_2 - I_1(x,y) - I_3(x,y)\right)\right]^2} 
$$

(6)

For the depth value of each point, it can be calculated by using Equation (7) [12].

$$
z(x,y) = c_0(x,y) \left[\phi(x,y) - \phi'(x,y)\right]
$$

(7)

where, $z(x,y)$ is the depth value of each point in the image, and $c_0(x,y)$ is a constant value that can be found by doing calibration using Equation (8). $\phi(x,y)$ and $\phi'(x,y)$ are the object’s phase and the reference phase.

$$
c_0(x,y) = \frac{z(x,y)}{\left[\phi(x,y) - \phi'(x,y)\right]}
$$

(8)
where, $z(x,y)$ is the height value, in this case, it is 3 mm.

![System depth calibration diagram](image)

**Figure 4.** System depth calibration

The calibration of the systematic parameters is calculated using the standard plane object where the height is known. The calibration requires a calibration plate, as shown in Figure 5. The camera captures the calibration plate at multiple known heights and the systematic parameter of matrix $A$ in Equation (10) [11]. In this case, the least-square approximation method is approached. Equation (9) can be expressed as Equation (10).

$$ m_i = A m_w $$

(9)

$$ \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} $$

(10)

where, $m_i$ represents the digital coordinate, $A$ is the systematic parameters, and $m_w$ is the world coordinate. The overall process for calibration of the system parameters is as shown in Figure 6.
2.5. Data collection

The setup for data collection is as shown in Figure 1. Two sets of fringes, 6-pixel width fringe and 120-pixel width fringe are projected on the sample and obtained. The image that contains the 120-pixel width fringe will undergo Median Blur filter and Gaussian Blur filter [14, 15], whereas the image that includes the 6-pixel width fringe will only undergo Median Blur. The phase calculation is calculated using Equation (4), and phase unwrapping is done using Equation (5). Phase check will be done, using Equation (6), to ensure that the phase modulation’s index is high. After that, the height, z(x,y), will be calculated using Equation (7), where c(x,y), ϕ(x,y), and ϕ'(x,y) is known. The XY coordinate of the sample is calculated by solving Equation (10), where the matrix A, x, y, and zw are known. The process is summarised in Figure 7.

3. Result and Discussion

The accuracy and the repeatability of the system is evaluated by using a calibration plate that is scanned from 0 µm to 1,000 µm with an increment of 50 µm. Each height is being captured 30 times. The sample used for this test is as shown in Figure 9. The red line is drawn on top of the calibration plate in Figure 9 is the line of interest where the height is being analysed. The result of calibration for the range of interest in different captured height parameters is shown in Figure 10. On the other hand,
another test is conducted using the precision ground steel bladed feeler gauge set (Figure 8) for the height accuracy test.

**Figure 8.** Precision ground steel bladed feeler gauge set

**Figure 9.** Calibration plate

Even though the graph in Figure 10 shows high frequency, it can be seen that the shape of the graph are consistent, where it is able to show the slight surface unevenness and the surface porosity of the ceramic plate. This shows that the system has a very consistent data acquisition and also has a high repeatability. Not only that, the graph also shows a very consistent height increment, which is the elevation of the height by 50µm.

**Figure 10.** Height of plate captured for 30 times on each level

Table 1 tabulated the mean of the obtained height for each different captured height. Table 1, the maximum percentage error of this system is 15.76%, which is 9.3511 µm in error. The minimum percentage error is 0.15%, which is 0.7339 µm. The result has shown that it is within the tolerance range of percentage error. The error for the first height, 0 µm, is not considered as the smallest error because that is the point used to offset the data to 0. The error of this data may also be caused by the
accuracy of the gauge system used to adjust the height of the calibration plate. In addition, the gauge system is also manually adjusted, and hence the human error may occur.

Table 1. Mean for obtained height for each level

| Expected mean height (µm) | Actual mean height (µm) | Error (µm) | Percentage Error (%) |
|---------------------------|-------------------------|------------|----------------------|
| 0                         | 0                       | 0          | 0.00                 |
| 50                        | 59.3511                 | 9.3511     | 15.76                |
| 100                       | 102.8822                | 2.8822     | 2.80                 |
| 150                       | 165.6513                | 15.6513    | 9.45                 |
| 200                       | 215.3133                | 15.3133    | 7.11                 |
| 250                       | 259.7878                | 9.7878     | 3.77                 |
| 300                       | 318.7217                | 18.7217    | 5.87                 |
| 350                       | 371.4360                | 21.4360    | 5.77                 |
| 400                       | 403.8041                | 3.8041     | 0.94                 |
| 450                       | 445.7006                | 5.7006     | 1.28                 |
| 500                       | 500.7339                | 0.7339     | 0.15                 |

Table 2 shows the result of scanning the feeler gauge set, which is usually used for calibrating the thickness or gap widths. This feeler gauge set has an accuracy of 12 µm. The maximum percentage error is 2.12%, which is 2.1671 µm. The minimum percentage error is 0.59% which is about 1.1703 µm. From Table 2, it can be seen that smaller expected height and bigger expected height in measurements will give a relatively big percentage error. However, this percentages error is lesser than 2.2% which can be neglected in system. The result in Table 1 shows high similarity with the result in Table-II.

Table 2. Mean height of each feeler gauge

| Expected Height (µm) | Mean Height (µm) | Error (µm) | Percentage Error (%) |
|----------------------|------------------|------------|----------------------|
| 100                  | 102.1671         | 2.1671     | 2.12                 |
| 200                  | 198.8291         | 1.1703     | 0.59                 |
| 400                  | 406.1227         | 6.1227     | 1.51                 |
| 550                  | 554.9294         | 4.9294     | 0.89                 |
| 800                  | 809.6683         | 9.6683     | 1.19                 |
| 1100                 | 1122.2656        | 22.2656    | 1.98                 |

Figure 11 depicts the standard deviation of the height captured at each level. This test is done by 30 repeated test for each level, which brings about 330 times repeated test. Based on this 330 times repeated test, the system has shown the result of standard deviation of the system to be within 7 µm. This shows that the system has quite a consistent height calculation. The minimum and maximum standard deviation is 2.4991 µm and 6.8886 µm, respectively. The high frequency can be seen from Figure 11 could be due to surface unevenness or the limitation of the projector.
The 3PSP method is used to 3D scan a washer that is being held down using a tape. Figure 12 shows the depth map of the washer that was scanned. It can also be seen that there is incomplete scan of the washer due to the specular surface. This is because the FPP method is not suitable to scan samples with a high dynamic range of surface reflectivity [8]. However, the 3D image reconstructed shows a good acquisition of the white masking tape, which is used to hold the washer.

4. Conclusion
This paper has presented the accuracy and stability of this setup. In this experiment, the three-step phase-shifting method is used. The result also shows maximum percentage error of 15.76%, and the maximum error is 22.2656. Hence, the accuracy of this system can be said to be within 23 µm. Although the data obtained shows high-frequency changes, the consistency of the system is within 7 µm. Future work can address the 3D acquisition of sample with high dynamic range of surface reflectivity and the method to remove the high-frequency noise which is able to maintain the accuracy of the measurement.

5. Reference
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