Single shot 3D profilometry by polarization pattern projection

YUUKI MAEDA, SHUHEI SHIBATA, NATHAN HAGEN, and YUKITOSHI OTANI*

Utsunomiya University, Center for Optical Research and Education, 7-1-2 Yoto, Utsunomiya, Tochigi 321-8585, Japan
*Corresponding author: otani@cc.utsunomiya-u.ac.jp

Received 11 November 2019; revised 31 December 2019; accepted 3 January 2020; posted 13 January 2020 (Doc. ID 382690); published 14 February 2020

We demonstrate a uniaxial 3D profilometry system illuminating the sample with a linear polarization pattern and measuring a polarization camera. The linear polarization pattern is generated by a spatial light modulator and a quarter-wave plate in the optical system. The system can measure four different fringe patterns with a phase difference of 90 deg simultaneously in the polarization camera. Therefore, we can measure three-dimensional shapes in a single shot. We present the measurement principles of the system and show the results of a real-time 3D profilometry experiment.

© 2020 Optical Society of America

https://doi.org/10.1364/AO.382690

1. INTRODUCTION

The fields of manufacturing inspection, medical inspection, robot vision, etc., have a need for high-precision, high-speed, and high-resolution measurements of the shapes of objects in 3D. Non-contact profilometry is particularly useful for preserving the surface quality during measurement. Whereas some profilometers aim to measure surface height features in the micrometer or nanometer range (surface roughness measurements) [1], the profilometry system that we propose here aims to measure samples with surface height variations in the millimeter range. For this type of measurement, the most common techniques are probably projection-based stereo optical systems in which axes of the projection system and imaging system are not coaxial. These include the light-section method [2], the moiré method [3], and the fringe projection method [4–6]. These stereo optical methods, however, have difficulty measuring inside deep holes or nearby large step heights. In these cases, uniaxial 3D profilometry methods are more practical.

An alternative approach to surface profilometry is uniaxial fringe projection. While a stereo fringe projection system uses the estimated fringe phases to infer the surface height, uniaxial 3D profilometry uses the change in fringe contrast as a function of defocus to detect height information. Neil et al. used phase shifting with fringe projection methods to perform optical sectioning and determined the change in fringe contrast with focus [7]. Takeda et al. proposed to use the contrast dependence on focus to perform 3D profilometry for opaque samples [8]. A 3D profilometry based on this principle was performed [9,10].

All of these fringe projection techniques need to collect multiple measurements in order to measure the surface profile. One modified approach uses the three colors (R, G, B) in a color camera to obtain three phase shift images simultaneously, from which one can estimate the surface profile in a snapshot [11]. Samples with spatially varying color, however, will cause artifacts in the measurements, so we propose an alternate technique that instead makes use of polarization instead of color to encode the contrast information. Using polarized light thus provides an alternative method for colored samples. The polarization-based approach integrates a polarization camera [12,13] into a uniaxial fringe projection system, so that the four polarization orientations captured simultaneously by the camera allow snapshot 3D profile measurements from four phase shift images.

2. EXPERIMENTAL SETUP AND MEASUREMENT PRINCIPLES

The system measures the contrast of the light reflected from a sample using a spatially varying polarization pattern and a polarization camera. Figure 1 shows the experimental setup, consisting of a uniaxial projection system and an imaging system. The polarization camera in the imaging system is composed of a micropolarizer array and detector array, where the micropolarizers are oriented at the four azimuth angles of 0°, 45°, 90°, and 135°.

The projection system produces the spatially varying polarization pattern using a quarter-wave plate (QWP) and a spatial light modulator (SLM). Starting from the light source, laser light is scattered by a rotating diffuser and collimated by lens L1. The rotating diffuser reduces speckle noise in the detected image, while L1 produces a collimated beam diameter matched to the SLM and objective lens L3. The collimated light is linearly polarized by polarizer LP and directed toward the SLM by the non-polarizing beam splitter.
Figure 2 shows a closeup of the beam near the SLM, showing the polarization state of the beam before and after the SLM. The linearly polarized light (step 1) is converted into circularly polarized light (step 2) by the QWP oriented at 45° to the beam’s linear polarization angle. The circularly polarized light incident on the SLM is converted into spatially varying elliptically polarized light (step 3) by varying the phase delay across the SLM. As the return beam passes through the QWP again, the elliptical states are converted back into linear polarization, but this time with spatially varying orientation angle (step 4). This linear polarization pattern is projected on the sample by lenses L2 and L3.

The polarization pattern reflected from the sample is imaged onto the polarization camera’s detector array through lenses L3 and L4. Figure 3 shows how the spatially varying linear polarization pattern incident on the micropolarizer array generates a set of four phase-shifted fringe patterns through each of the four micropolarizer orientations in the array.

We can characterize the linear polarization pattern (step 4 of Figure 2) quantitatively using Mueller calculus. Passing the input Stokes vector $S_{in}$ from the light source (which we assumed to be unpolarized) through each of the optical elements in turn...
gives the output Stokes vector $S_{out}$ projected onto the sample given by

$$ S_{out}(x, y) = \text{QWP}(-45^\circ) \cdot \text{SLM}(\phi(x, y), 0^\circ) \cdot \text{QWP}(45^\circ) \cdot \text{LP}(0^\circ) \cdot S_{in} $$

$$ = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r_r + r_p & 0 & 0 & 2\sqrt{r_pr_p} \cos(\phi(x, y)) \\ 0 & r_r - r_p & 0 & 2\sqrt{r_pr_p} \sin(\phi(x, y)) \\ 2\sqrt{r_pr_p} \sin(\phi(x, y)) & -2\sqrt{r_pr_p} \cos(\phi(x, y)) & 0 & 0 \\ 0 & 0 & 0 & 2\sqrt{r_pr_p} \cos(\phi(x, y)) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} $$

$$ = \frac{1}{2} \begin{bmatrix} r_r + r_p \\ r_r - r_p \\ 2\sqrt{r_pr_p} \sin(\phi(x, y)) \\ 2\sqrt{r_pr_p} \cos(\phi(x, y)) \end{bmatrix}, $$

where $\phi(x, y)$, $r_r$, and $r_p$ represent the phase applied to the SLM, and the reflectances of $s$- and $p$-polarized light from the SLM. If we substitute $r_r = r_p = 1$ in Eq. (1), $S_{out}$ becomes

$$ S_{out} = \begin{bmatrix} \cos(\phi(x, y)) \\ \sin(\phi(x, y)) \end{bmatrix}. $$

From Eq. (2), we see that the azimuthal angle of linear polarization, given by $\tan^{-1}(S_2/S_1)$, is equal to the phase $\phi(x, y)$ of the SLM. Thus the spatially varying angle of polarization is controlled simply by adjusting the phase $\phi(x, y)$ at each column across the SLM.

The light intensity $I(x, y, \psi)$ detected by the polarization camera is given by

$$ I(x, y, \psi) = d^T P(\psi) \cdot S_{out} $$

$$ = \frac{1}{2} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \cos(2\psi) \\ \sin(2\psi) \cos(2\psi) \\ \sin(2\psi) \sin(2\psi) \\ \sin^2(2\psi) \\ \sin(\phi(x, y)) \end{bmatrix} $$

$$ = \frac{1}{2} \{ 1 + \gamma_0(x, y) \cos(\phi(x, y) - 2\psi) \}, $$

where $P(\psi)$ is the Mueller matrix of a micropolarizer oriented at angle $\psi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\}$, and $\gamma_0(x, y)$ is the ideal contrast, defined by

$$ \gamma_0 (x, y) = \frac{2r_r r_p}{r_r^2 + r_p^2}. $$

From Eq. (3), we can obtain four phase-shifted patterns at once from the detected intensity by the polarization camera by separately analyzing the images behind the four micropolarizer orientations. The contrast $\gamma(x, y, z)$ and the phase $\phi(x, y, z)$ are calculated by applying a four-step phase-shifting technique to the measured intensities:

$$ \gamma(x, y, z) = \frac{2\sqrt{(I_0 - I_{90})^2 + (I_{45} - I_{135})^2}}{I_0 + I_{45} + I_{90} + I_{135}}, $$

$$ \phi(x, y) = \tan^{-1}\left(\frac{I_{45} - I_{135}}{I_0 - I_{90}}\right), $$

where $I_0, I_{45}, I_{90},$ and $I_{135}$ are

$$ I_0 = I(x, y, z, 0^\circ), \ I_{45} = I(x, y, z, 45^\circ), $$

$$ I_{90} = I(x, y, z, 90^\circ), \ I_{135} = I(x, y, z, 135^\circ). $$

Equation (4) shows that the contrast $\gamma(x, y, z)$ can be measured in a snapshot from the four phase-shifted images. For a non-polarizing sample, the contrast as a function of the sample surface's distance from focus takes the form of a Bessel function that can be approximated as a Gaussian function [10]. The contrast is maximum when the height of the sample is at the best focus position of the optical system. During system calibration, we can fit the parameters of a Gaussian function to height $z$ as

$$ \gamma(x, y, z) = \gamma_0(x, y) \exp\left(-\frac{1}{2}\left(\frac{z - z_0}{\sigma}\right)^2\right). $$

Inverting Eq. (6) gives the surface height as a function of contrast:

$$ z(x, y) = z_0 + \sigma \sqrt{2 \ln \left(\frac{\gamma_0(x, y)}{\gamma(x, y, z)}\right)} \quad (z \geq z_0), $$

$$ z(x, y) = z_0 - \sigma \sqrt{2 \ln \left(\frac{\gamma_0(x, y)}{\gamma(x, y, z)}\right)} \quad (z \leq z_0). $$

By measuring the contrast distribution using a planar reference sample in advance, we can calibrate parameters $\gamma_0(x, y), z_0,$ and $\sigma$ in Eq. (6). For calibration, the reference sample should
produce a contrast profile (change with height that is proportional to that of the measurement sample, and which shares the measurement sample's polarization characteristics). These conditions are easily satisfied if the reference and measurement sample surfaces are made of the same material, but this is not the primary requirement. Note that the contrast profile is symmetric about $z_0$, so that this method cannot by itself distinguish between heights in the range of $z \geq z_0$ from those in $z \leq z_0$ using Eq. (7) or Eq. (8) alone. However, if we set up the measurement such that we ensure the sample heights only occur in the positive range for $z - z_0$, then this is not a problem.

Because all four of the phase measurements needed for the contrast estimate are obtained in a snapshot, this method can measure three-dimensional profiles in a single shot. Because the optical transfer function of a fringe projection system is expressed in the form of the Bessel function \[8\], the measurable range of $z$ (mm) is given by

$$0 \leq z - z_0 \leq \frac{M \cdot F}{\pi \cdot N} \quad (z \geq z_0)$$

or

$$-\frac{M \cdot F}{\pi \cdot N} \leq z - z_0 \leq 0 \quad (z \leq z_0) ,$$

where $F$ is the $F$-number of the optical system, $N$ is the number of fringe patterns per millimeter, and $M (= 3.832 \ldots)$ is the first zero of the Bessel function $f_1$.

### 3. EXPERIMENTAL RESULTS

In order to demonstrate the system, we performed two experiments on reference samples. For the experiments, we chose lens focal lengths for $L_1$, $L_2$, $L_3$, and $L_4$ of 30 mm, 100 mm, 20 mm, and 200 mm. A $f$-number of the optical system is about $f/15$. The light source is a 532 nm Nd-YAG laser. The SLM is a liquid-crystal-on-silicon type with a $792 \times 600$ grid of 20 $\mu$m pixels (X10468, Hamamatsu Photonics K.K.). The polarization camera has a $2064 \times 1560$ grid of 2.5 $\mu$m pixels. Therefore, the lateral range of the system is 0.51 mm $\times$ 0.39 mm.

For our first experiment, we measured a plane mirror as a sample in order to validate the grating patterns detected by the polarization camera. Figure 4 shows the phase map of the SLM and the result of reshaping the phases of the fringes reflected from the plane mirror, using Eq. (5). We confirmed the phase changes linearly from $-180^\circ$ to $180^\circ$ along the y-direction. The phase map is used to generate the linear polarization pattern on the sample to obtain the proper four kinds of fringe patterns.

Figure 5 shows the image collected by the polarization camera, as seen by each of the four orientations of micropolarizer pixels. We can see clearly phase shift between each of the four images. Figure 6 shows the projected image captured by the ordinary camera has a uniform distribution, but we can see the fringe pattern from the projected image captured by the ordinary camera through the linear polarizer.

Next, we measured the contrast of a plane mirror while the plane mirror was translated in 0.2 mm intervals by a $z$-axis stage. Figure 7(a) shows the measurement results of the contrast fitted by a Gauss function, and Fig. 7(b) shows the calibrated height of the $z$-axis stage and versus the height estimated using Eq. (7).

![Fig. 4.](image-url)

(a),(b) Wrapped phase map of the SLM pattern and its cross-sectional view. (c),(d) Wrapped phase map and cross-section view, measured by the polarization camera using Eq. (5), for a flat reference sample.

![Fig. 5.](image-url)

Images detected for each polarizer orientation in the polarization camera.

![Fig. 6.](image-url)

(a) Projected image on the sample captured by the ordinary camera (without micropolarizers). (b) Projected image on the sample captured by the ordinary camera viewing the scene through the linear polarizer.
Fig. 7. (a) Measured contrast as a function of the sample height, and the fitted Gauss function (red curve). (b) Relationship between the sample height and the height estimated by the fitted Gauss function.

(a) Stepped sample
(b) Cross section(A-B)

(c) 0 ms  (d) 33 ms  (e) 66 ms  (f) 99 ms

Fig. 8. Results of the real-time 3D profile measurements of the step sample: (a) the stepped sample. (b) Cross section of the measured profile at four time points. The vertical axis gives the surface height for time $t = 66$ ms, and the other time points are vertically offset for clarity. (c)–(f) 3D profile of the step sample at time points 0 ms, 33 ms, 66 ms, and 99 ms (see Visualization 1).
For heights within the range of 0.3–2.4 mm, the average height error is 0.04 mm. Therefore, the depth range of the system is 2.1 mm, and the resolving power (the number of resolvable elements) along the $z$-direction is 2.1 mm$/0.04$ mm $= 52$.

Next, we measured the 3D profile of the moving stepped sample to demonstrate real-time 3D profilometry, the results of which are shown in Fig. 8. During the experiment, the stepped sample is translated along the $x$-axis using a linear stage. The polarization camera captures the data at 30 fps and the image size at the sample is 0.48 mm $\times$ 0.28 mm. The thickness of mirrors M1 and M2 is 1.0 mm. The height is calculated from the measured contrast using the calibrated curve of the reference plane mirror (Fig. 7).

4. CONCLUSION

The real-time uniaxial 3D profilometry system we demonstrate here fulfills a need for high-precision, high-speed, and high-resolution measurements of the shapes of objects in 3D. A previous method for doing this employed color diversity to capture three fringe patterns in a snapshot, but this can cause artifacts for objects with spatially varying color features. Here we use a polarization camera and polarization pattern projection, which is accurate for objects having spatially homogeneous polarization properties. This adds another technique to the toolbox of engineers designing profilometry systems, and delivers 3D data at a frame rate limited only by the speed of the camera. The uniaxial construction of the measurement gives an advantage for measuring deep holes and large step heights—features that are difficult for stereo projection systems to measure.

The system we demonstrate here is suitable for samples with height variations in the millimeter range, but this can be adjusted for larger height ranges by using larger projection optics, or for smaller height features by using a higher numerical aperture objective lens. For a given SNR, the height resolving power (calculated as 52 above) remains the same regardless of the projection optics. This system is well-suited to evaluate shapes of a sample composed of a single material. However, the problem of this system is that it cannot measure a sample composed of materials with different depolarization because the contrast depends on the depolarization.

Disclosures. The authors declare no conflicts of interest.

REFERENCES