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A demonstration of structured-illumination-based technique using commercial surgical endoscope

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Abstract

An integration of commercial surgical endoscope using structured illumination technique for three-dimensional reconstruction was performed on biological samples with a depth of field of 20 mm and a relative accuracy of 0.1%.

1. Introduction

Structured illumination (SI) technique is a classical method for depth-resolved measurement. Instead of searching for disparity correspondence, SI detects phase distribution from the fringe deformity on the object, and relates the phase information to depth measurement. The technique simplifies the depth calculation compared to the use of disparity searching and therefore reduces computational cost. To further investigate SI performance in an endoscopic view, we introduce an SI endoscopic imaging setup which provides a wide FOV that addresses quantitative depth information and can be integrated with commercially available endoscopes to provide tissue profilometry. Furthermore, by adapting our previous flexible camera calibration method for the 3D reconstruction technique in free space [1, 2], we developed an optimal fringe pattern for capturing the inner tissue profile within the endoscopic view and validated our method using both static and dynamic biological samples that exhibit a DOF of approximately 20 mm and a relative accuracy of 0.1%.

2. Method

Our setup displayed in Fig. 1 comprises of a digital light projector (TIDL VP3000, Texas Instrument, Dallas, Texas, USA), a charge-couple-device (GS3-U3-15S5M-C, Point Grey Research Inc., Richmond, Canada) and two identical rigid surgical endoscopes (0-degree, 5-mm-diameter scope, Karl Storz GmbH & Co. KG, Tuttlingen, Deutschland). The projected fringes from the projector are coupled into a lens L1 (RMS4X, Thorlabs, Newton, New Jersey, USA) to feed into the illumination scope. These fringes once reflected off the sample's surface become distorted and provide associated phase information of the sample.

The collected distortion is then focused through an achromatic doublet lens L2 (AC254-060-A, Thorlabs, Newton, New Jersey, USA) to the camera sensor. To minimize triangulation noise and overall form-factor of the endoscope, a minimum angle of 15 degrees is maintained to separate the illumination and the imaging scopes.

The projected fringe pattern is given as:

$$I_i(u, v) = I_o \left[1 + \cos\left(\frac{2\pi k u}{w} + \delta\right) \right]. \quad (1)$$

where I_o is the intensity modulation amplitude, δ the shifted phase, k the fringe number, (u, v) are the spatial pixel indices, w the pattern width. From the collected fringed patterns, the wrapped phase ϕ_n^w of each obtained image is calculated using the conventional four-step phase shift method and then unwrapped as following:

$$\phi_n(u, v) = \phi_n^w(u, v) + 2\pi \cdot \left\lfloor \frac{\phi_{n-1} \frac{k_n}{k_{n-1}} - \phi_n^w}{2\pi} \right\rfloor. \quad (2)$$

where ϕ_n is the unwrapped phase, ϕ_n^w wrapped phase, and $n = \{1, 2, 3, 4\}$ the n -th of the selected frequencies.

The sample's height z at pixel index (u, v) is related to the unwrapped phase as in Eq. (3):

$$z = \frac{c_o + c_1\phi + (c_2 + c_3\phi)u + (c_4 + c_5\phi)v + (c_6 + c_7\phi)u^2 + (c_8 + c_9\phi)v^2 + (c_{10} + c_{11}\phi)uv}{d_o + d_1\phi + (d_2 + d_3\phi)u + (d_4 + d_5\phi)v + (d_6 + d_7\phi)u^2 + (d_8 + d_9\phi)v^2 + (d_{10} + d_{11}\phi)uv}. \quad (3)$$

where c_{0-11} , d_{0-11} are constants determined by geometrical parameters from camera calibration, ϕ is the unwrapped phase distribution of the fringe pattern with the highest frequency.

3. Results and discussion

The system was first validated with a standardized target with known depth increments (DOF 5–15, Edmund Optics, York, UK). The maximum depth error is 0.043 mm and the maximum standard deviation is of 0.114 mm within the range of 10 mm measured depth. We then performed 3D imaging on biological samples of *ex-vivo* porcine intestine and an *in-*

vivo human mouth cavity. The natural shape and features on both sample are well-indicated in the 3D maps (Fig. 2).

Due to the angle of separation between the two scopes, future design should focus on the integration of the two scopes into one using angle prisms, or on the optimization of the optical component at the distal end of the endoscopes for an adequate overlapped regions imaged by the two scopes.

4. Conclusion

The results provide evidence of using commercial surgical endoscope in structured-illumination for reconstructing 3D surfaces of biological samples.

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Fig. 1.
Plenoptic endoscopic system.

Fig. 2.
Top: Porcine intestinal specimen with its corresponding 3D shape. Bottom: Human mouth cavity and its reconstructed 3D shapes at different viewing angles.