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3-D endoscopic imaging using plenoptic camera

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Abstract

Three-dimensional endoscopic imaging using plenoptic technique combined with F-matching algorithm has been pursued in this study. A custom relay optics was designed to integrate a commercial surgical straight endoscope with a plenoptic camera.

1. Introduction

Our previous work demonstrated an ex-vivo optimal suture mapping method using multi-spectral image based tissue classification for intestinal anastomosis surgery [1]. However, to guide a surgical robot for autonomous surgery, a stereoscopic view with a precision depth perception that could profile tissue's biological characteristic onto its structural profile through an endoscope is needed. During a surgical operation, endoscopic imaging capable of capturing the depth and contour of the target anatomical structure is crucial in evaluating risk and assessing treatment [2]. Many 3D endoscopic techniques have been explored and improved in medical imaging to collect structural profiles with high resolution and sensitivity, such as the structured illumination method [3]. However, the delivery of structured light with distinct fringes requires a second light probe, equipped in another laparoscope. An alternative approach, and the objective of this study, is called the plenoptic technique. The plenoptic technique utilizes a micro optical array in front of a camera sensor to acquire images of the object of interest at different perspectives. However, due to the small aperture of the commercial endoscope compared to the micro lenses, gaps between neighboring micro images result in low resolution of the depth profile. Consequently, a relay optics is necessary to match F-numbers of the endoscope to the micro lens array of the plenoptic camera. We propose a relay lens integrating a commercial surgical endoscope and a 3D plenoptic camera, while maintaining the F-matching criteria.

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2. Method

The system setup described in Fig. 1 consists of three sections: the light ray transport, the detection, and the illumination section. The light ray transport section consists of a commercial 0° endoscope with a housing diameter of 10 mm (Stryker, San Jose, California, USA). The detection site is a Raytrix 3D light field camera (R5, Kiel, Germany) equipped with a microlens array with a manufactured opening aperture of F/2.4. The object is illuminated with halogen light coupled into the endoscope light port. A biconvex lens with focal length of 25 mm was used to focus the reflected light out of the eyepiece of the endoscope into a beam spot. This beam spot is then expanded to be collimated to the front surface of another biconvex lens with focal length of 40 mm (F-40). The collimating length is maintained by an identical F-40 lens, which helps tracing the beam light through the micro lenses to the plenoptic sensor. The distances between the chosen lenses are optimal to match the focal length of the commercial microlens array in front the sensor. Calibration and depth analysis are implemented using commercial RxLive 2.8 and MatLAB 2015a software.

3. Results and discussion

We first experimented with the planar surface of a checkerboard and demonstrated the subtle changes between planar tilting angles (Fig. 2a), along with the focused plane in normalized density scatter plots (Fig. 2b) in comparison with the commanded tilting angles.

We then proceeded with the plenoptic imaging of more complex structures made from polydimethylsiloxane material with different depth resolutions and curvatures. Sample 1 in Fig. 3b has an L-shape plane raised from a curved base with raised height of 12mm. Sample 2 in Fig. 3c has a small cylinder post (2-mm post diameter) located on a circular base and staircase with 1-mm step size. A checkerboard with each side length of 8 mm is a planar reference, whose depth image endorses no gradient across its surface; however, the grid contour maintains. In addition to the planar checkerboard sample, plenoptic imaging results of both curved samples reflect the shape of the specimens, with surface fluctuations indicated in the depth-resolved colormap.

A compensation of Fresnel light reflection should be considered during the endoscopic surgery. Fresnel reflection occurs when incoming light travels from ambient air (refractive index $n = 1$) to a higher refractive index of the specimen (typically $n > 1.33$ due to water-based tissue property of mammalian internal organ), which creates intensity saturation, or glare, on the collected image. This event can be diminished using a polarizer and analyzer to selectively admit only incoming light at the Brewster angle to the tangent surface of the biological sample.

4. Conclusion

Three-dimensional endoscopic using plenoptic approach has been demonstrated with planar and inhomogeneous samples. Continued development will focus on integrating both multispectral tissue characterization and 3D profiling to support the optimal suturing during an intestinal anastomosis surgery.

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Fig. 1.
Plenoptic endoscopic system.

Fig. 2.

(a) Micro images of checkerboard at tilting angles of 0, 15 and 45 deg along z-axis (bar scale: 5 mm); **(b)** the normalised density scatter plot of checkerboard point clouds and the commanded tilting angle plane (magenta line).

Fig. 3. Micro images of (a) a checkboard, (b) Sample 1 and (c) Sample 2 along with (d-f) their depth-resolved image, respectively. Colormap marks the quantized relative depth in millimeter.