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Endoscopic Application of a Compact Compound-Eye Camera

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Abstract

A multi-functional compound-eye endoscope enabling multi-spectral imaging and variable field-of-view is presented, which is based on a compact compound-eye camera called TOMBO (thin observation module by bound optics). Narrow-band filters attached to some lenses provide snap-shot multi-band images. Fixed and movable mirrors are introduced to control the field of view, which realizes several observation modes such as three-dimensional shape measurement, wide field-of-view, and close-up observation.

Abstrak

Penggunaan Kamera Bermata Majemuk Rapat di dalam Endoskopi. Telah diciptakan sebuah endoskop bermata majemuk multifungsi yang memungkinkan pencitraan multispektral dan zona pandang yang bervariasi. Kamera ini dibuat berdasarkan kamera bermata majemuk rapat yang disebut TOMBO (modul observasi tipis dengan optik terikat). Filter yang berbentuk berkas tipis dipasang pada sejumlah lensa dan menghasilkan citra-citra multiberkas yang berbasis jepretan foto. Kamera ini juga menampilkan cermin-cermin yang posisinya konstan atau dapat digeser untuk mengatur zona pandang, yang memungkinkan penggunaan sejumlah moda observasi seperti pengukuran bentuk tiga dimensi, zona pandang yang luas, dan observasi jarak dekat.

Keywords: compound-eye camera, multi-spectral imaging, polarization imaging, wide field-of-view

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I. Introduction

Importance of endoscopic screening and surgery has been greatly increasing. Capsule endoscopes [1] and NOTES (natural orifice translumenal endoscopic surgery) [2] have opened a door to easy complete diagnosis and little invasion in surgery. To obtain more information in operation, multi-modal observation such as flexible spectral imaging color enhancement (FICE), narrow band imaging (NBI), hyperspectral imaging, near-infrared (NIR) imaging, and auto-fluorescent imaging as well as three-dimensional shape measurement providing the distance and the scale of subjects is attracting more attentions recently.

An application of a thin and compact compound-eye camera called TOMBO (thin observation module by bound optics) [3] to endoscopes has been proposed to realize highly-functional three-dimensional endoscopes [4,5]. Medical applications of TOMBO such as three-dimensional multispectral endoscopes [4] and intra-oral shape measurement [6] have been investigated. These works mainly focused on obtaining the three-dimensional shape of subjects from a compound-eye image. TOMBO endoscopes include the features of stereoscopic endoscopes [7,8] and also offer several additional advantages. It is well known that depth estimation with a multi-baseline stereo method, where more than two cameras are used, improves accuracy of estimation. Furthermore, multi-lens design allows systems to acquire multi-dimensional optical information such as multispectral images [9] that provide information of tissues or blood vessels, and polarization [10] for controlling the observable depth.

In this paper, multi-spectral imaging by narrow-band filters attached to some lenses in the TOMBO is presented. Fixed and movable small mirrors are introduced to obtain controllability of the field of view. The field of view of conventional TOMBOs was not large enough to satisfy the requirement in endoscopes because the complexity of the lens (e.g. the number of elemental lenses) was limited by the volume of camera. With these mirrors, the line of sight can be folded to switch between a parallel configuration that provides narrow filed-of-view but is suitable for three-dimensional shape measurement, and a cross configuration that achieves wide field-of-view for far objects and multi-viewpoint close-up observation for near objects.

2. Experiment

Overview of Tombo and Tombo Endoscope: Structure. Figure 1 and 2 show examples of the TOMBO endoscope and its basic structure, respectively. TOMBO is composed of a single imager and a lens array. TOMBO provides an array of elemental images including three-dimensional information as disparities. One of the most important features of TOMBO is functional extension by attaching optical components to lenses. This feature enables TOMBO to acquire multiple images in different modes simultaneously (e.g. different wavelengths or polarization) without suffering from a time lag due to a motion of the camera or objects. Based on pattern projection with a small diffractive optical element (DOE), a single-mode optical fiber, and a collimator introduced through the forceps port, distances at several points can be retrieved quickly. To achieve a large depth of field, e.g. 5-100 mm, required in endoscopes, a wave front coding technique (WFC) [11] is utilized in TOMBO endoscopes [12]. This technique is also effective even with a fast optics.

Processing. Figure 3 shows a typical processing flow of TOMBO endoscopic systems. To achieve deep focus by fast lenses, the obtained compound-eye image is blurry due to WFC. Firstly, the blur is eliminated by inverse filtering or iterative methods with calculated or measured point-spread functions (PSFs) that are assumed to be independent of the distance because of WFC so that a deeply-focused fine image is obtained. By extracting two elemental images in the deblurred compound-eye image, simple stereoscopic display is realized. To reproduce a high-resolution single image of the subjects, unification and elaborate deblurring considering small dependency of the PSF on the depth are required. A depth map or a three-dimensional shape of subjects is estimated based on a passive multi-baseline stereo method [13]. Then, super-resolution processing [14] unifies all the elemental images in the compound-eye image to a single image with the PSFs that reflect their slight dependency on the depth. Consequently, a three dimensional model of the subjects is built on a computer. Operators can observe it on the stereo display from any view point.

Multispectral imaging. Figure 4(a) and (b) show the alignment of band-pass filters and a photograph of the fabricated filter array, respectively. Table 1 shows specifications of the camera. Figure 5(a) is an example compound-eye image. Because disparities are included in the compound-eye image, emulation of focusing is possible after capturing on a computer, which is called

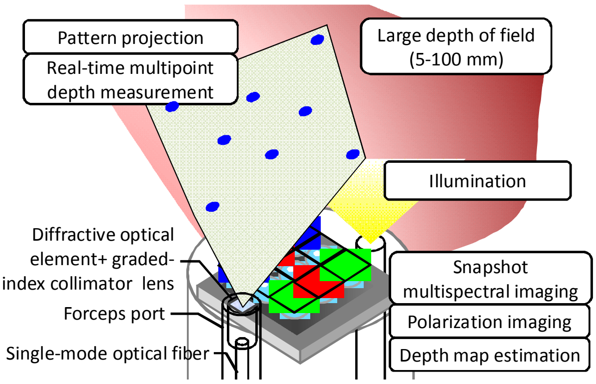


Figure 1. An Example of TOMBO Endoscope

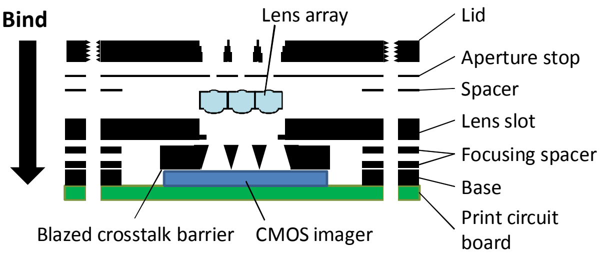


Figure 2. An Example Structure of TOMBO

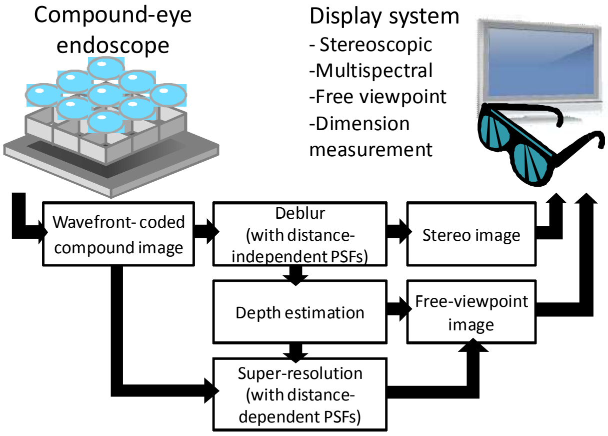


Figure 3. Typical Processing of TOMBO Endoscopic System

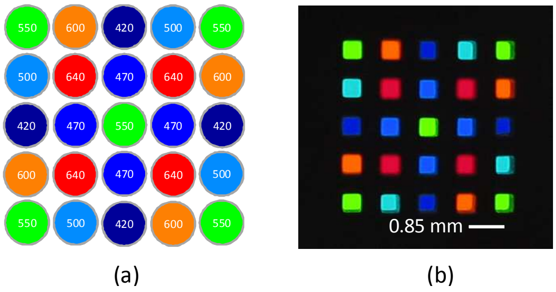


Figure 4. (a) Alignment of Band-Pass Filters and (b) a Fabricated Filter Array

refocus. Refocused images are obtained as shown in Figure 5(b) and (c). In Figure 5, there are two objects; the background object is a color chart, and the foreground is a glass figure. The refocused distances in Figure 5(b) and (c) are 0.67 m and 0.12 m, respectively. Figure 6 shows a set of multi-spectral images after processing to remove the disparity. A set of the 6-band multi-spectral image was successfully obtained.

Variable field-of-view polarization compound-eye endoscope. Figure 7 shows the structure of the proposed TOMBO endoscope. There are 3×3 lenses, and the lines of sight of the 8 lenses in the peripheral are folded by the fixed mirrors. They are surrounded by 8 movable mirrors, which can select one of the two positions for parallel (Figure 8(a)) and cross (Figure 8(b)) configurations by the actuators. The full field of view is limited to about 40 degrees for a single lens with acceptable aberrations. The movable mirrors are effective to achieve the field of view more than 100 degrees required in endoscopes. The cross configuration provides a multi-viewpoint close-up observation mode for near objects, which is suitable for observing fine structure of the surface.

Table 1. Specifications of Multi-Spectral TOMBO

Lens array	5×5
Lens pitch [mm]	0.85×0.85
Focal length [mm]	2.35
Pixel count per lens	128×128
Band-pass filters (peak/band width in FWHM)	420/50, 470, 500/52, 550/52, 600/69, 640


(a) (b) (c)

Figure 5. (a) A Compound-Eye Image and Refocused Images at Distances of (b) 0.67 m and (c) 0.12m

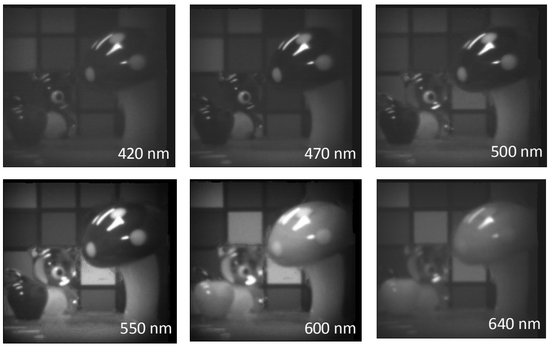


Figure 6. A Set of a 6-band Multi-Spectral Image After Disparity Removal

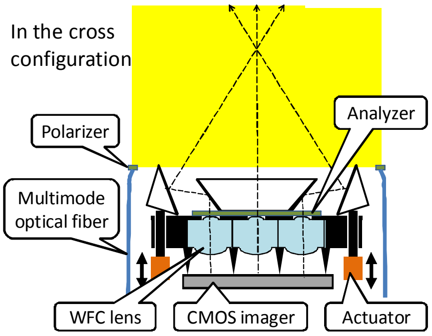
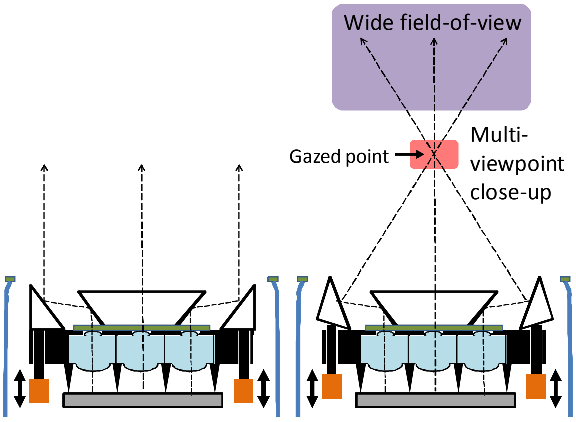


Figure 7. (a) Configuration of the Proposed Variable Field-of-View TOMBO Endoscope



(a) (b)

Figure 8. (a) Parallel and (b) Cross Configurations

3. Results and Discussion

Simulation and experimental results. Expansion of the field of view and close-up observation were verified by simulation. Figure 9 depicts the optical setup. Table II summarizes the specifications of the TOMBO endoscope, where the TOMBO is assumed to be composed of commercially-available products so far.

Expansion of field-of-view. An object (an image of cow's stomach) shown in Figure 10 was placed 50-100mm away from the TOMBO. In the parallel configuration, the reconstructed area was smaller than the original object as shown in Figure 11 because the total field of view was limited by that of each lens for far objects. On the other hand, in the cross configuration, whole object was successfully reconstructed.

Multi-angle close-up observation. An object shown in Figure 12 was placed around 10 mm away from the TOMBO. As shown in Figure 13, in the parallel configuration, disparities were so large that each lens saw mostly different part of the object. However, in the cross configuration, every lens saw the center of the object. Figure 14 compares original and estimated [12] depth maps. Most part of the depth map corresponds very well. The uncertain region could be caused by occlusion.

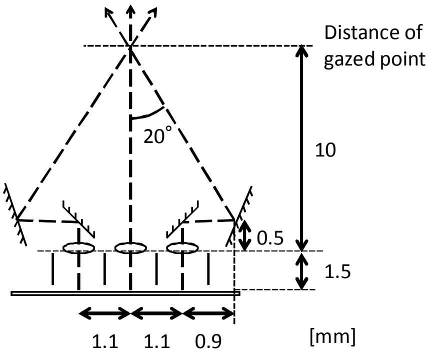


Figure 9. Configurations of TOMBO Endoscope in Simulation

Table 2. Specifications of TOMBO Endoscope

Focal length (mm)	1.5
Full field of view (degree)	35
Number of lenses	3x3
Lens pitch (mm)	1.1
Pixel pitch (μm)	2.2

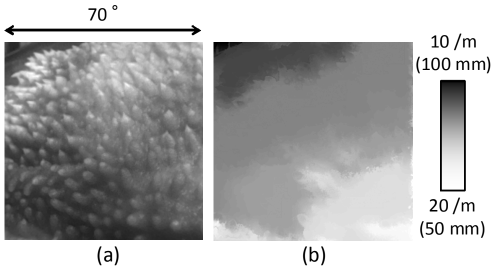


Figure 10. (a) Texture and (b) Depth Map of a Far Object

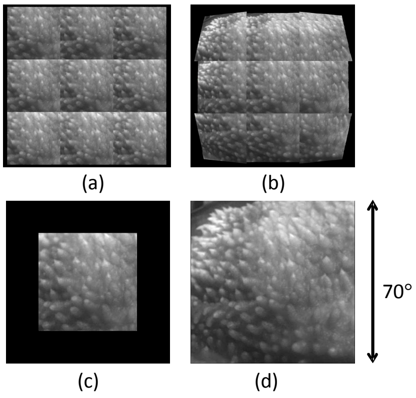


Figure 11. Compound-Eye Images for (a) Parallel and (b) Cross Configurations. Reconstructed Single Images at Distance of 15/m (67 mm) for (c) Parallel and (d) Cross Configurations

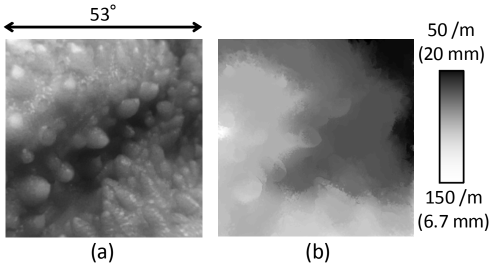


Figure 12. (a) Texture and Depth Map of a Near Object

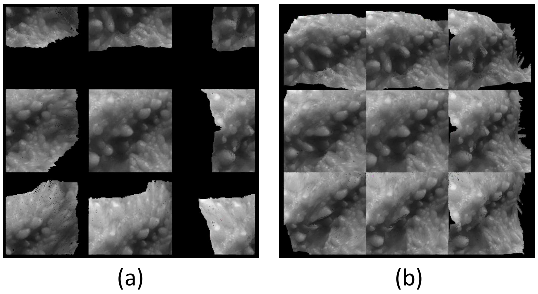


Figure 13. Compound-Eye for Images (a) Parallel and (b) Cross Configurations

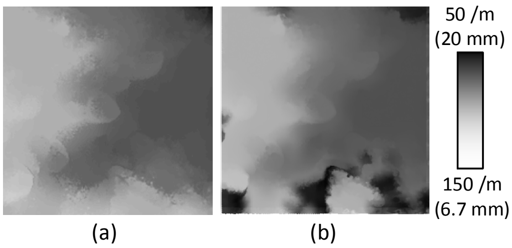


Figure 14. (a) Original Depth Map (the Same as Figure 12(b)) and (b) Estimated Depth Map from Figure 12(b)

4. Conclusions

A compound-eye endoscope with band-pass filters and variable field-of-view was presented. Fixed and movable mirrors were introduced to control the field of view. The proposed endoscope has several observation modes that are defined by the field-of-view. Expansion of the field of view and a close-up multi-angle observation were verified by simulation.

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