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Variable field-of-view visible and near-infrared polarization compound-eye endoscope

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Abstract— **A multi-functional compound-eye endoscope enabling variable field-of-view and polarization imaging as well as extremely deep focus is presented, which is based on a compact compound-eye camera called TOMBO (thin observation module by bound optics). Fixed and movable mirrors are introduced to control the field of view. Metal-wire-grid polarizer thin film applicable to both of visible and near-infrared lights is attached to the lenses in TOMBO and light sources. Control of the field-of-view, polarization and wavelength of the illumination realizes several observation modes such as three-dimensional shape measurement, wide field-of-view, and close-up observation of the superficial tissues and structures beneath the skin.**

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, 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. Combination of these mirror configurations and polarization as well as illumination wavelength, selection of several observation modes becomes possible. In the proposed TOMBO endoscopic system, polarization is controlled not at the lenses but by the multiple small light sources to obtain the compatibility with conventional endoscopes.

II. Overview of TOMBO and TOMBO Endoscope

A. 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. 5mm-100mm, required in endoscopes, a wavefront coding technique (WFC)[11] is utilized in TOMBO endoscopes[12]. This technique is also effective even with a fast optics.

B. Processing

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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.

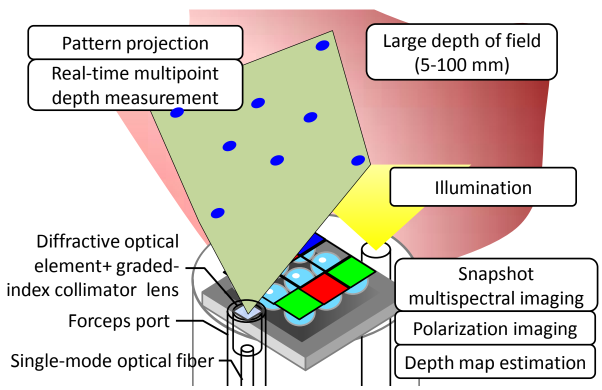

Fig. 1. An example of TOMBO endoscope.

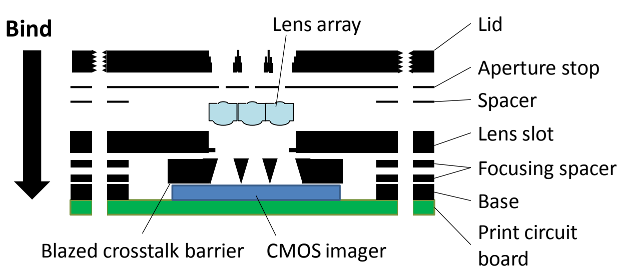

Fig. 2. An example structure of TOMBO.

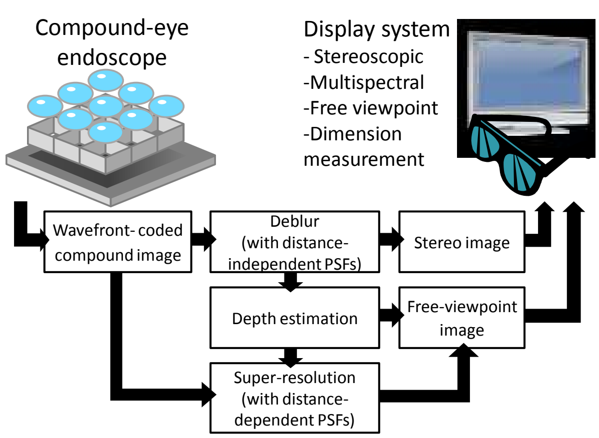

Fig. 3. Typical processing of TOMBO endoscopic system.

III. Variable Field-of-View Polarization Compound-eye Endoscope

A. Structure

Figure 4 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 (Fig. 5(a)) and cross (Fig. 5(b)) configurations by the actuators. Users can switch these two configurations according to their requirements in observation. However, note that no scanning is necessary for the mirrors. 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.

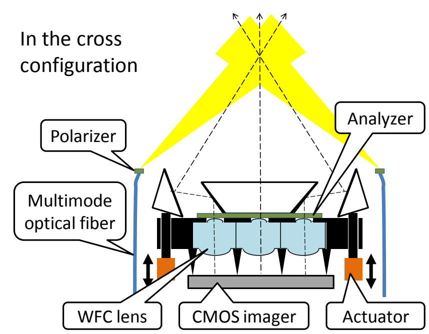

Fig. 4. (a) Configuration of the proposed variable field-of-view TOMBO endoscope.

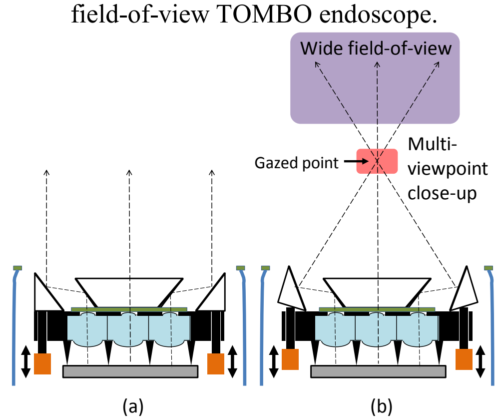

Fig. 5. (a) Parallel and (b) cross configurations.

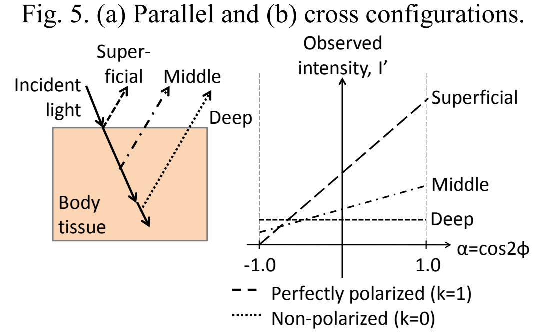

Fig. 6. Polarization break caused by scattering and observed intensity.

B. Polarized observation

When illumination is linearly polarized and scattered light by biological tissues is observed with a analyzer, an observed light intensity $I'(\alpha)$ is written by

$$I'(\alpha)=\frac{1}{2}\sum_{i=1}^{N}(1+\alpha k_i)E_i \quad (1)$$

$$\alpha=\cos 2\varphi . \quad (2)$$

Note that φ means a difference between the orientations of polarization of the illumination and the analyzer. N is the number of objects. k_i and E_i are degree of polarization break caused by scattering in the tissues and the luminance of the object i. k_i ranges from 0 to 1. For the non-polarized light, k_i is 0, and for the perfectly-polarized light, k_i is 1. Figure 6 illustrates Eq. 1. By controlling φ, contrast of the superficial and deep structures can be controlled. Figure 7 shows examples of stomach cancer observed with polarizers. In observation, metal-wire grid polarizer film is utilized. Therefore, both of visible and NIR lights can be used. The NIR light whose wavelength fits the absorption peak of hemoglobin or fluorescent material is suitable for observation of deep structures.

Polarized light sources are located as shown in Fig. 8,

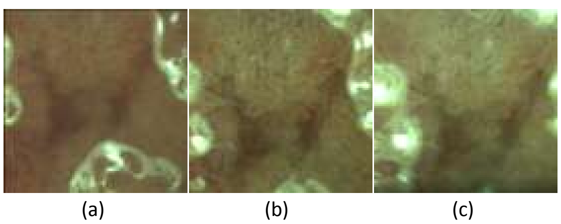

Fig.7. Example images of polarization observation of stomach cancer for (a) φ=90°, (b) φ=45°, and (c) φ=0°.

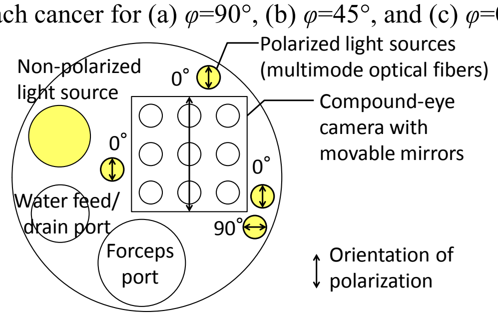

Fig. 8. Schematic drawing of the top view.

Table I. Observation modes for far objects.

Observation mode	Illumination	
	Wavelength	Polarization
Normal	Visible	Non-polarized
Deep	NIR	
(Auto)fluorescent	UV	

Table II. Observation modes for near objects.

Observation mode	Illumination	
	Wavelength	Polarization
Normal	Visible	Non-polarized
Deep	Visible/ NIR	90 degree
(Auto)fluorescent	UV	Any
Superficial	Visible	0 degree

which are used to illuminate objects only around the gazed point. Therefore, small light sources such as multi-mode optical fibers (e.g. 50 -100 μm core) are suitable. Measurement of surface morphology of tissues is achieved by observing superficial backscattered light by changing the position of the light source. To determine the three-dimensional orientation of the surface, three light sources whose polarization angle is 0 degree are prepared.

C. Observation modes

Tables I and II summarize observation modes. The observation modes of the proposed TOMBO endoscope is defined by wavelength (ultraviolet/ visible/ NIR) and polarization (0-degree/ 90-degree/ none-polarized) of the illumination, distance of subject (close-up/ far), and convergence (parallel/ cross).

IV. 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 III summarizes the specifications of the TOMBO endoscope, where the TOMBO is assumed to be composed of commercially-available products so far.

A. Expansion of field-of-view

An object (an image of cow's stomach) shown in Fig. 10 was placed 50-100mm away from the TOMBO. Note that the depth maps and the textures in Figs. 10 and 12 were estimated with cow's stomach based on the multi-baseline stereo method. In the parallel configuration, the reconstructed area was smaller than the original object as shown in Fig. 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.

B. Multi-angle close-up observation

An object shown in Fig. 12 was placed around 10 mm away from the TOMBO. As shown in Fig. 13, in the parallel

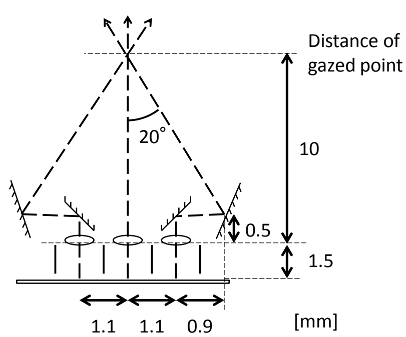

Fig. 9. Configurations of TOMBO endoscope in simulation.

Table III. Specifications of TOMBO endoscope.

Focal length [mm]	1.5
Full field of view [degree]	35
Number of lenses	3 × 3
Lens pitch [mm]	1.1
Pixel pitch [μm]	2.2

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.

V. CONCLUSION

A compound-eye endoscope with variable field-of-view and polarized illuminations was proposed. Fixed and movable mirrors were introduced to control the field of view. Contrast of superficial and deep structures are controlled by the polarization of small light sources. The proposed endoscope has several observation modes that are defined by the field-of-view, polarization and wavelength of the illumination. Expansion of the field of view and a close-up multi-angle observation were verified by simulation.

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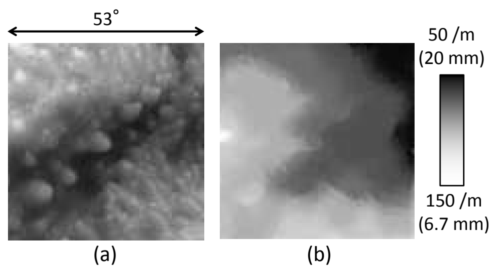

Fig. 12. (a) Texture and depth map of a near object.

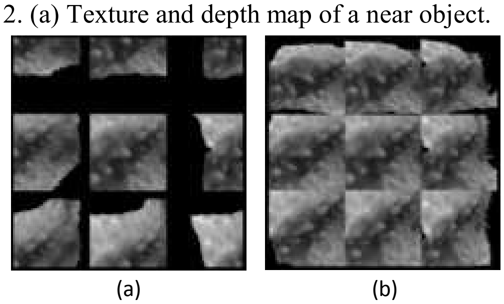

Fig. 13. Compound-eye for images (a) parallel and (b) cross configurations.

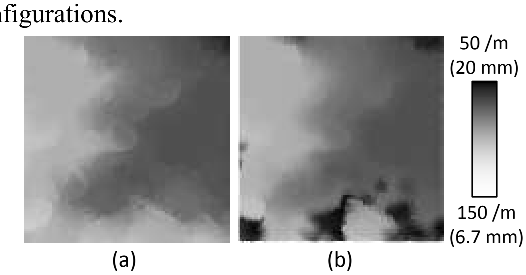

Fig. 14. (a) Original depth map (the same as Fig. 12(b)) and (b) estimated depth map from Fig. 12(b).

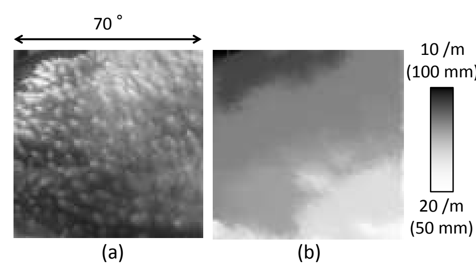

Fig. 10. (a) Texture and (b) depth map of a far object.

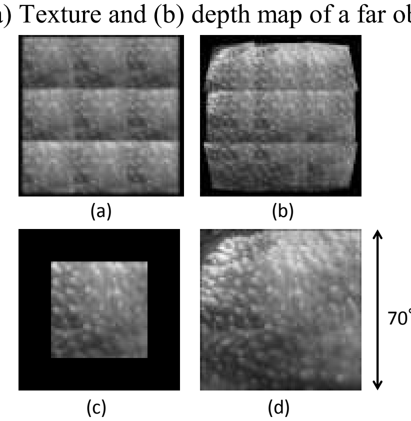

Fig. 11. Compound-eye images for (a) parallel and (b) cross configurations. Reconstructed single images at distance of 15/m (67 mm) for (c) parallel and (d) cross configurations.