3D SHAPE RECONSTRUCTION ENDOSCOPE USING SHAPE FROM FOCUS

T. Takeshita[1], Y. Nakajima[1, 2], M. K. Kim[1], S. Onogi[2], M. Mitsuishi[1] and Y. Matsumoto[1, 2]
[1]*School of Engineering, the University of Tokyo, Tokyo, Japan*
[2]*Intelligent Modeling Laboratory, the University of Tokyo, Japan*

Keywords: Three-dimensional Endoscope, Three-dimensional Reconstruction, Shape from Focus.

Abstract: In this paper, we propose three-dimensional (3-D) shape reconstruction endoscope using shape from focus/defocus (SFF/SFD). 3-D shape measurement that uses the endoscope image sequence can measure both the shape and the texture at the same time. It has some advantages such as the analysis of lesion location that integrates the analysis of shape and texture. And the shape and the texture from the endoscope can be recorded quantitatively. To obtain 3-D information, shape measurement methods using stereo cameras is often used. But in case of narrow space, 3-D reconstruction using focus information such as SFF/SFD is more appropriate in terms of apparatus size. Therefore, we apply SFF method to endoscope for shape reconstruction, and conducted two basic experiments to confirm the possibility of the system using general camera as a first step. First, to estimate the accuracy of shape measurement of the system, shape measurement of the objects that the shape is already-known was conducted. And the error of the system was calculated about 1 to 5 mm. Next, to confirm the possibility to measure biological inner wall, the measurement of inner wall of the pig stomach was conducted, and the shape was reconstructed.

1 INTRODUCTION

Endoscope is medical equipment to examine or to treat the inner part of body where the direct observation cannot be done from the outside. In general, obtained information from an endoscope is two-dimensional (2-D) information. One of the drawbacks of present endoscopy is lack of depth information. However, the depth information is indispensible to accurate endoscopic diagnosis. The aim of this paper is 3-D recovery of inner shape of organ from endoscopic image sequence. Therefore, quantitative shape and the texture on the surface of inner part of organ can be measured at the same time during operation. The 3-D shape reconstruction endoscope offers various advantages from the feature. To begin with, the analysis of lesion location based on the analysis of shape and texture becomes possible. Recently, several researchers have been proposed automatic polyp detection. These are mainly classified into two approaches. First one uses shape information by computed tomography (CT) (Vining DJ et al., 1994) and the other uses texture information by endoscope image.
(D. K. Iakovidis et al., 2005)

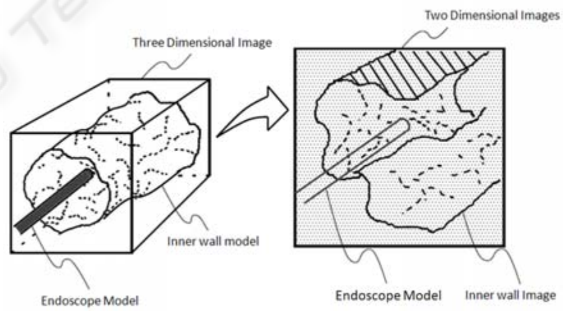


Figure 1: Formation of focused and defocused images.

For the 3-D measure endoscope can measure the shape and the texture at once, it could be possible to analyze polyps more accurately. Second, it becomes easier to integrate with preoperative 3-D data from CT. Next, viewpoint can be changed virtually with 3-D surface. So with the 3-D reconstruction endoscope, the operation can be performed more safely. Moreover, the inner shape of organ information can be recorded by this endoscope.

Several researchers have applied computer vision techniques to recover 3-D information from endoscope image sequence. 3-D shape recovery

Takeshita T., Nakajima Y., Kim M., Onogi S., Mitsuishi M. and Matsumoto Y. (2009).
3D SHAPE RECONSTRUCTION ENDOSCOPE USING SHAPE FROM FOCUS.
In *Proceedings of the Fourth International Conference on Computer Vision Theory and Applications*, pages 411-416
DOI: 10.5220/0001804004110416

methods by stereo camera measurement (D. Stoyanov et al., 2005), laser scanning (M. Hayashibe et al., 2006), shape from shading methods (T. Okatani et al., 1997), illumination model (P. Sánchez-González et al., 2008) and shape from motion methods (K. Deguchi et al., 1996) (T. Nagakura et al., 2007) have been presented for clinical applications of endoscope. Stereo camera measurement and laser scanning have drawback for endoscopic operations in terms of the size of endoscope because it needs two or more optical system or additional laser devices. Shape from shading makes use of the Lambertian reflectance model that brightness is constant regardless of the observed angle. But it is difficult to satisfy the constraint in many cases of real organ surface. Shape from motion solves for 3-D shape by using the relative motion of objects from the camera. However, for achieving 3-D measurement, it requires the perturbational camera motion for image acquisition of different positions.

We propose a configuration for 3-D shape recovery of endoscopic images based on shape from focus (SFF). Figure 1 is a schematic diagram of concept of our method. In SFF method, shape is obtained with the use of the image sequence partially in-focus taken by changing the focused position. The analysis of focus to estimate depth from the camera to object has been used for the automatically focusing camera system. The auto focus method from focus information using the Fourier transform is proposed by Horn(B. K. P. Horn, 1968). Several methods concerning the analysis of focus criterion are compared by Krotkov(E. P. Krotkov, 1987). And the method of recovering shape from focus has been presented by Nayar(S. K. Nayar et al., 1994) and Subbarao(M. Subbarao et al., 1994).

Although SFF is not available for many cases, it is appropriate for endoscopic inspection and therapy because of several reasons. Considering invasion and pain of patients, endoscopes need to be narrow. SFF is a method for extracting 3-D shape for single camera and can make its hardware configuration compact. Unlike the stereo method, SFF needs neither matching problem nor occlusion, so the application to a wide-angle lens suitable for an endoscope is easy. Another account is that lighting condition is easily controlled inside of organ rather than outside world. It is an advantage to fulfill strict conditions for SFF.

2 METHOD

2.1 Shape from Focus

SFF is a method of measuring shape by using focus information. The focused position depends on the camera parameters such as lens position or image sensor.

The geometry of the defocusing and focusing can be expressed by Figure 2. In this Figure, *di* is the distance between the lens and sensor plane, *df* is the distance between the lens and the focal plane when the focus is perfectly focused. In case of *df'>df* or *df'<df*, namely, if object is not placed on Focused point, blur circle is formed. SFF method is an application of this principle.

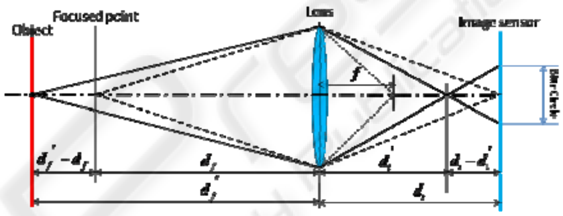


Figure 2: Formation of focused and defocused images.

The steps of SFF process are following. First, two or more pictures are taken by changing the image sensor position, the lens position or the object position. In this paper, lens position is varied for image sequence. Second, the focus measures of each pixel in the each image are compared, and the camera parameters are estimated by which the photographed object is perfectly focused. Finally, we can obtain the depth of each point from the camera parameters.

2.2 Computation of Focus Measure

In SFF, it is important to evaluate the degree of focus measure, and have proposed various methods. In this paper, we use to evaluate focus measure using High-Pass Filter (HPF) is introduced by Krotkov (E. P. Krotkov, 1987) and Nayar (S. K. Nayar et al., 1994). The blur image is represented image intensity function $i(x, y)$. $i(x, y)$ is expressed by the convolution of Point Spread Function(PSF) $h(x, y)$ and perfectly focused image $i_f(x, y)$.

$$i(x,y) = h(x,y) * i_f(x,y) \qquad (1)$$

In equation (1), the symbol "*" denotes convolution. By considering the defocusing process in the frequency domain, we obtain the following equation.

$$I(u,v) = H(u,v) \cdot I_f(u,v) \quad (2)$$

Where $I(u, v)$, $H(u, v)$ and $I_f(u, v)$ is the Fourier transforms of $i(x, y)$, $h(x, y)$, and $i_f(x, y)$. 2-D Gaussian function is used for an approximation of the PSF (A. Pentland, 1987), (S. K. Nayar et al. 1994). By approximating $h(x, y)$ with 2-D Gaussian function.

$$h(x,y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2} \right) \quad (3)$$

The Fourier Transform of PSF is called Optical Transfer Function (OTF) of camera system and is given as

$$H(u,v) = \exp\left(-\frac{u^2 + v^2}{2} \sigma^2 \right) \quad (4)$$

Consequently, from equation (4) and (5), $I(u, v)$ can be expressed as

$$I(u,v) = \exp\left(-\frac{u^2 + v^2}{2} \sigma^2 \right) \cdot I_f(u,v). \quad (5)$$

At the same time, σ (spread parameter) is thought to be proportional to the defocusing radius in the PSF. Therefore, the more images become defocused, the more the power spectrum of high frequency gets attenuated. And if the frequency is higher, the degree of attenuation is larger. For this reason, defocusing can be considered as Low Pass Filter that attenuates high spatial frequency. Hence, analyzing the high frequency power spectrum enables us to estimate the degree of defocus.Using this point, HPF can be used to estimate focus measure. Laplacian filtering is one of the methods of high pass filtering (E. P. Krotkov, 1987). The Sum of absolute values of convolution is used as focus measure.

We use Laplacian of Gaussian (LoG) instead of Laplacian for the purpose of reducing the effect of CCD's noise and analyzing focus measure. Following equation (6) is focus measure function f_m we used.

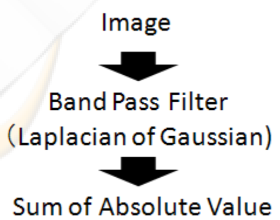


Figure 3: Computation of Focus Measurement.

$$f_m(i,j) = \sum_{x=i-\frac{N}{2}}^{i+\frac{N}{2}} \sum_{y=j-\frac{N}{2}}^{j+\frac{N}{2}} | LoG(x,y) * i(x,y) | \quad (6)$$

$LoG(x, y)$ is represents the LoG filter. And $i(x, y)$ is image intensity function. N is the window size of the summation. (i, j) is the position in the image. The computation process of focus measure is shown in Figure 3.

2.3 Depth from the Lens Position

The best focus lens position at each point in the image is acquired through changing the lens position. But the relation between the lens position and the focal plane is necessary to calculate the depth.We can estimate the relation by the Gaussian lens law for the thin lens as the following equation. Figure 4 shows the relation between the lens position and the focal plane. In equation (5), f is the focal length.

$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f} \quad (7)$$

From equation (7), we can obtain following equation (8).

$$d_1 = \frac{f d_2}{d_2 - f} \quad (8)$$

In equation (8), f depends on the lens and is a constant parameter. In Figure 4, d_2 is determined by the camera settings, that is lens position and sensor position. So depth can be computed if these camera parameters are found. The result of the computed depth and measured depth is shown in Figure 5.

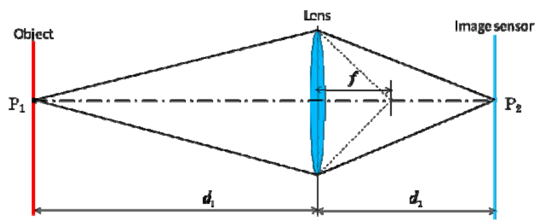


Figure 4: Geometry of imaging.

3 EXPERIMENTAL RESULTS

We implemented SFF for recovering the shape of tilted plate, cylinder and inner wall of pig stomach by general camera not endoscope shown as Figure 6 as a first step to apply the shape recovering method to endoscope. The difference between the camera and the endoscope is scale. But for the purpose of

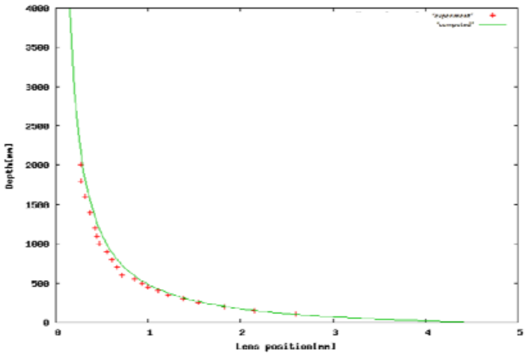


Figure 5: Focused position as a function of lens position.

confirming the possibility of our method, it is considered to be possible.

Both the plate and the cylinder are covered with checkerboard pattern. And these are estimated in order to evaluate the accuracy of our system. In addition, we selected stomach of pig as body inner wall model. And then depth information of stomach is acquired by SFF.

Figure 6 shows a photograph of the experimental apparatus used to demonstrate the DFF method. A few images are obtained using a CCD camera with 620x480 pixels and the lens that the focal length is 25mm and the f-number is 1.4. And Camera images are digitalized and processed using a computer.

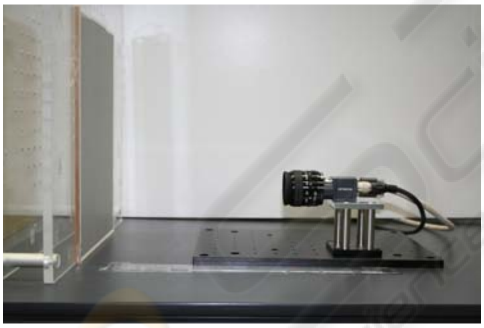


Figure 6: Camera and board posted with checkerboard pattern. Moving the camera relative to the board, the relation between the lens position and focused position is obtained experimentally.

3.1 Shape Estimation of Cylinder and Plate

In the first experiment, we estimated the accuracy of our SFF system. The condition of this experiment is following: From camera to object distance is 30mm.

Diameter of cylinder is 59mm and degree of tilted plate is 45. And we use page of 40 sheets sequence image. This set-up of experiment is shown as Figure 7.

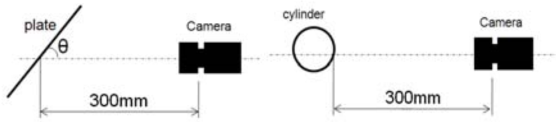


Figure 7: Experimental set-up.

The result of experiments is shown in Figure 8, 9. And RMS and Max error of depth map is shown in Table1.

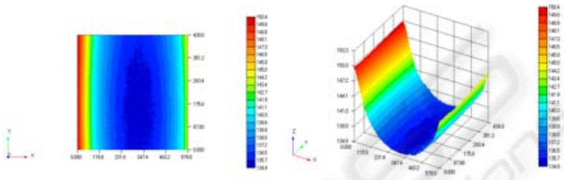


Figure 8: (a) Frontal image of depth of cylinder. (b) Lateral image of depth of cylinder.

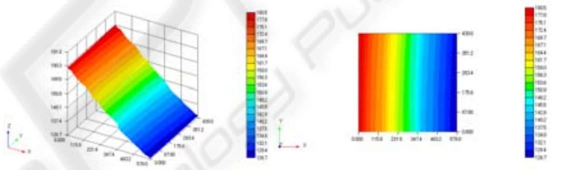


Figure 9: (a) Frontal image of depth of tilted plate. (b) Lateral image of depth of tilted plate.

Table 1: RMS and max error of depth map.

Object	RMS Error [mm]	Maximum Error [mm]
Plane	0.873	3.63
Cylinder	1.19	4.11

3.2 Biological Object

We implemented measurement of inner wall of pig stomach as an example of inside body measurement. Inner wall of pig stomach is shown as Figure 10 and Figure 11.

Figure 12 shows acquired depth map from measurement. The color is expressed as real depth. The result of texture mapping images by depth map and all focused image is expressed Figure 13. All focused image mentioned above is made of each pixel which has best focus measure by equation (6).

Considering the result of texture mapping, the shape of inner wall of pig stomach is reconstructed successfully in terms of shape recovery. And we can obtain the shape and texture information at once.

Figure 10: Image of inner wall of pig stomach.

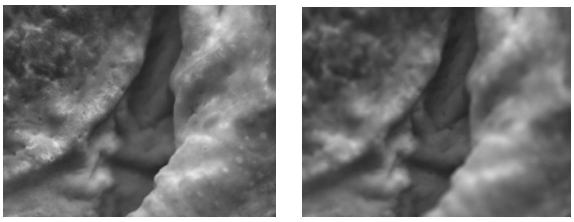


Figure 11: Example of images used for calculation. The two images are taken with different camera setting.(Lens position).

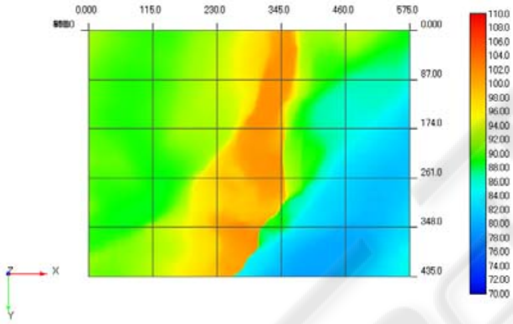
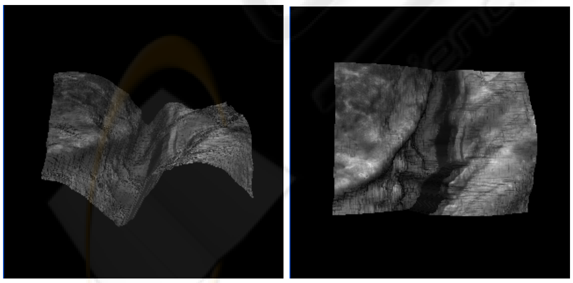


Figure 12: Depth map of inner wall of pig stomach.



(a) Frontal shape (b) Lateral shape

Figure 13: The result of texture mapping by Figure 11, 13.

4 DISCUSSION

4.1 Accuracy Improvement

In the 3D shape measurement using SFF, depth of field (DOF) is one of the most important factors to determine the accuracy of measurement physically. The smaller the DOF becomes, the more the depth resolution rises. Therefore, the optimization of the optical parameters is necessary in SFF measurement.

In the shape measurement experiment of the biological object, the spatial resolution is considered to be decreased. It is thought that in the equation 6, the window size N causes the effect. For improving, it is necessary to optimize the filter parameters used in the calculation of focus measure. The spatial resolution becomes high when the window size is decreased. On the other hand, the effect of noise becomes larger. So to determine the optimal parameter, it is needed to take these points into consideration.

4.2 Application for Endoscope

In experiments, we use a usual camera. But the verification with an endoscope shaped device is indispensable to actually apply it to the endoscope. However, we are examining the structure that not to install the system in an existing endoscope but to install the small camera able to move the lens or image sensor on the head of thin fiber. In this case, major difference with an actual endoscope is size. But the blur phenomenon is quite similar as shown in Fig.5. Therefore, we think that the miniaturized system can measure the shape similarly if the optical geometry is equivalent.

We assume that the system is used in the diagnosis such as polyp detection. But about forty images are used to calculate the depth map shown in Fig.13. In this case, the high speed camera is thought to be needed.

5 CONCLUSIONS

We have presented a 3-D shape reconstruction endoscope using SFF. And we conducted experiments to estimate the accuracy of shape measurement and confirmed qualitatively to be able to measure the shape of the biological object.

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