3D endoscopic system based on active stereo method for shape measurement of biological tissues and specimen

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***Abstract*—For endoscopic medical treatment, measuring the size and shape of the lesion, such as a tumor, is important for the improvement of diagnostic accuracy. We are developing a system to measure the shapes and sizes of living tissue by active stereo method using a normal endoscope on which a micro pattern projector is attached. In order to perform 3D reconstruction, estimating the intrinsic and extrinsic parameters of the endoscopic camera and the pattern projector is required. Particularly, calibration of the pattern projector is difficult. In this paper, we propose a simultaneous estimation method of both intrinsic and extrinsic parameters of the pattern projector. This simplifies the calibration procedure required in practical scenes. Furthermore, we have developed an efficient user interface to intuitively operate the calibration and reconstruction procedures. Using the developed system, we measured the shape of an internal tissue of the soft palate of a human and a biological specimen.**

I. INTRODUCTION

In recent development of endoscopy technology, diagnosis and treatment using endoscopes on digestive tracts have been widely performed. As for the treatment of gastric cancers of early stages, treatment methods differ based on the sizes of tumors. For this reason, accurate measurement of the sizes of tumors is important. Currently, major forceps are used to visualize the size of polyps, but it is prone to human errors. Therefore techniques for objective measurements are desirable.

We have developed an endoscopic system that enables 3D measurement [1], based on active stereo techniques using projection of a static pattern [2]. By attaching a micro pattern projector on a normal endoscope, we make it possible to measure the 3D shapes of target surfaces without altering the endoscope itself. With this technique, accurate and objective measurement of the sizes of the lesion part is achieved.

For this system, the endoscopic camera and the pattern projector requires calibration of intrinsic and extrinsic parameters, *e.g.*, the focal length, or the relative position of the projector. To achieve this, we have used the calibration method using planes [3], however, the plane based technique requires a large number of images for accurate calibration whereas the scaling parameter cannot be determined. To overcome the problem, we propose using a spherical shape as a calibration object with which only a few images are required and can determine the scaling. Another advantage of the method is that we can calibrate both the intrinsic and extrinsic parameters of the pattern projector simultaneously, not only the extrinsic parameters.

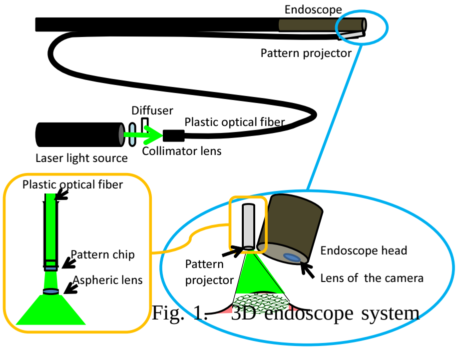

Fig. 1. 3D endoscope system

In the following sections, we describe the overall configuration of the 3D endoscope system, the user interface, calibration method of the parameters, and measurement results of biological tissues.

II. RELATED RESEARCH

In the method mentioned in [1], we estimated the internal parameters of the pattern projector by plane-based calibration using the surface of an LCD monitor; however this procedure was complicated. Furthermore, the focal length of the pattern projector may change, when the focal positions are adjusted or the wavelength of the light source is changed. The proposed method simplifies the procedure by estimating both the extrinsic and intrinsic projectors simultaneously using spheres. This simplifies the calibration process and enables us to deal with changes of the focal length of the projector.

For 3D reconstruction method using endoscopes, techniques using Shape from Shading (SFS) method [4] or using binocular stereo method [5] have been proposed. However, these techniques often require large limitation for image acquisition process, or require special endoscopes.

As an example that uses active stereo method, there is a technique that measures the shape by scanning with a single laser line from the head of lower gastrointestinal endoscope [6], but the head of the endoscope needs to be moved in parallel direction with respect to to the target; thus the applicable situation is heavily limited.

III. SYSTEM CONFIGURATION

Fig. 1 shows the configuration of the proposed system. For this system, a projector-camera system is constructed by

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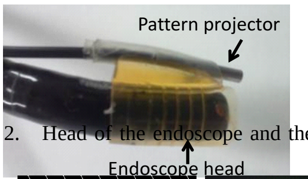
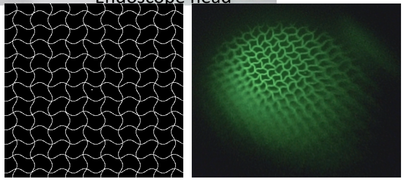


Fig. 2. Head of the endoscope and the pattern projector.



(a) (b)

Fig. 3. (a) The pattern image (wave grid pattern), and (b) a projected grid pattern.

attaching a micro pattern projector on an existing endoscope. The endoscope system used for our system is FUJI FILM's VP-4450HD and EG-590WR. As shown in fig. 2, the pattern projector is mounted on the head part of the endoscope using an attachment device provided by TOP corporation. The light source of the pattern projector is a green laser module with the wavelength of 532nm.

The laser light from the light source is transfered through plastic optical fiber (POF) and led to the head of the pattern projector. A micro pattern chip on which the pattern image is printed is set at the tip of POF. Lights that pass through the pattern chip also pass through the non-spherical lens placed in front of the chip and emitted to the target surface. According to the effect of the optics, the pattern on the chip is projected onto the target.

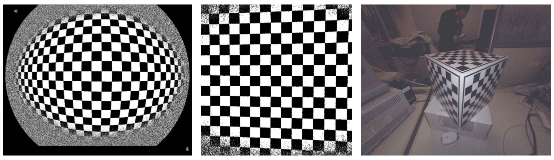
The head of the endoscope with the pattern projector attached is flexible. It can bend up and down 300 degrees and left and right 200 degrees. In order not to hinder the bending flexibility of the endoscope, the size of the head of the pattern projector is designed to be 2.7mm in diameter, and 14mm in length.

As shown in fig. 3(a), the pattern consists of grid pattern with wave lines in vertical and horizontal directions. Fig. 3(b) shows the actual image where the pattern is projected onto a planar object. By setting the wave length of the horizontal wave pattern not to be an integral multiplication of the horizontal interval of the vertical wave patterns, the pattern becomes locally unique for each grid points within the length of LCM; thus the local appearance can be used to find correspondences between the camera image and the projected pattern.

IV. SYSTEM CALIBRATION

A. Calibration of the endoscopy camera

Since the endoscopic camera captures wide range of view by using with fish eye lens, distortion by the fish eye lens should be corrected. As for the projection model of the fish eye lens of the endoscopic camera, we apply the equisolid angle projection. This model projects the point with θ angle in front of the camera to the distance with $2f\sin\theta$ from the image center. This model was adopted because we have tested several projection models which are known for fish eye lens and this model turned out to be the best accordance. Calibration detail is as follows. First, a set of data consisting of the 2D coordinates of the point on the LCD monitor and its projected position on the camera are acquired. To achieve this, Gray code pattern [7] is displayed on the LCD monitor and captured by the endoscopic camera at fixed position. This enables us to acquire a projection map between the LCD monitor and the image captured by the endoscopic camera. Fig. 4(a) shows an example of such map. Although peripheral parts of the captured image include noise, the area that has noise will not be used for further process.



(a)

(b) (c)

Fig. 4. Calibration of endoscopic camera: (a) map from monitor to endoscopic camera image, (b) undistorted map (only 2D projective transformation map remains), and (c) calibration object (undistorted).

Parameters for the equisolid angle projection is estimated from the map. The number of the parameters being estimated is three: f for the equisolid angle projection, and two for representing the image center. The parameters are estimated so that the undistorted map can be approximated by a 2D projective transformation. Fig.4 (b) shows the undistorted map using the estimated parameters. By using the estimated parameters, we were able to acquire an undistorted image of a cube-shaped calibration device as shown in Fig. 4(c). With this image, we can estimate the intrinsic parameters of the camera.

B. Calibration of the pattern projector

Pattern projector projects a static pattern to the 3D space. Since relationships between the projected point in the 3D space and the original 2D point on the static pattern for the projector are the same as those for the camera, the geometric property of the pattern projector and the camera are assumed to be the same. However, compared with a camera, a pattern projector can only acquire the correspondences between 3D points and 2D points of the projected pattern with indirect way. For this reason, calibration of a pattern projector is more difficult than a camera. In addition, the pattern projector that is used in our system cannot change the projected pattern and it makes the calibration harder. Recently, the method using the surface of the LCD monitor as a planar calibration device and by projecting the pattern on it to estimate the intrinsic parameter of the pattern projector is proposed [3]. However, this procedure was complicated since it requires a different camera other than the endoscopic one and also a surface of the LCD which is projected by the pattern projector from different positions should be captured multiple times.

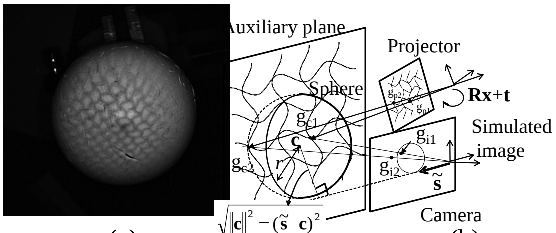
To overcome the above-mentioned problem, we use a spherical calibration device for calibrating both the intrinsic and the extrinsic parameters of the pattern projector. Since the method does not require an additional camera, the calibration procedure is simplified. In addition, since the estimation of extrinsic and intrinsic parameter is done simultaneously, users do not have to consider whether the intrinsic parameter of the pattern projector changes during the process. Note that this is a great advantage for a practical use since the structure of the pattern projector is simple with a single lens attached in front of the chip of printed pattern; thus, the intrinsic parameter (focal length) may easily vary by adjusting the lens to adjust focus. Furthermore, intrinsic parameter may change due to the change of the wave length of the laser light source.

Fig 5(a) shows the captured image of projected pattern onto the spherical object from the pattern projector with an endoscopic camera. The radius of the spherical surface is known and the image is undistorted by preprocess. From the image, points along the spherical contour are sampled. If more than three points are sampled, we can estimate the 3D position of the spherical surface of the camera. Furthermore, if we can find the position of the grid point projected onto the spherical surface from the captured image, by synthesizing sphere on the image, we can estimate the 3D position of the point. By acquiring the correspondence of the grid point on the image and the grid point on the pattern of the pattern projector, we are able to achieve correspondences between 2D coordinates on the pattern image and the 3D positions on the sphere. This enables us to calibrate the intrinsic parameters. Furthermore, since these 3D points are represented by the endoscopic camera coordinate system, the rigid transformation matrix for the camera and the pattern projector coordinates are simultaneously estimated, thus calibration of the extrinsic parameters is also achieved.

To improve the calibration accuracy during the actual calibration, bundle adjustment based on error minimization is applied by using the intrinsic parameters of the pattern projector, the extrinsic parameters and 3D coordinate of the center position of the spherical surface as the variables. If those variables are given, it is possible to project the grid points on the spherical surface to the camera image. The difference between the projected point and the 2D point detected from the captured image is the reprojection error (Fig. 5(b)). Also by retrieving the line of sight that corresponds to the points on the contour of the sphere with the camera coordinates, the line is tangent to the spherical object in 3D space; the distance between the spherical object and the line equals to the known radius. Based on this, the difference between the distance from the spherical object, calculated with the given variables, and the given radius is also considered to be an error (Fig. 5(b)). Thus, the sum of squares of these errors is minimized by using Levenberg-Marquardt method.

V. 3D RECONSTRUCTION

We apply the method proposed by Sagawa *et al.* as the 3D reconstruction method [8]. For 3D reconstruction, we project the wave grid pattern onto the object from the pattern projector, and then capture the object by an endoscopic camera. After the distortion of fish eye lens of the captured image is removed, Belief Propagation (BP) method is applied to extract the wave grid pattern from the image [9]. For all the intersections of the extracted wave grid pattern on captured image, points in the vicinity of epipolar line drawn on the patterned image are selected as the corresponding points.



(a) (b)

Fig. 5. Calibration of intrinsic/extrinsic parameters of the pattern projector by sphere object: (a) pattern projection on a sphere, (b) calibration errors.

Since multiple candidates are selected for intersection points on the camera image from the projected pattern, BP algorithm that utilizes connectivity is used to achieve single solution. At the end, since the correspondence between all pixels of the projected pattern and the captured image is acquired, depth values for all the pixels are estimated, and thus, dense 3D shape is reconstructed.

VI. USER INTERFACE

As already mentioned, we attach the micro pattern projector onto a common endoscope for each scan. The extrinsic parameters change every time when the pattern projector is attached to the endoscope, thus it requires to calibrate the parameters each time. Considering the actual usage in clinical sites, a user interface that enables us to intuitively operate image capturing system for calibration and reconstruction and procedures of calibration and reconstruction is needed. We made a GUI for the purpose as shown in Fig. 6.

With the GUI, users can capture the image with the endoscopic camera by just pushing the capture button and the captured image is consequently displayed on the monitor for check purpose. At the beginning of scanning, a static pattern is projected from the pattern projector onto the spherical object with known radius and then several images are captured by changing the position of the sphere. Several images are then selected for calibration by the GUI. The captured images are undistorted at this stage. In addition, sampling a number of points from the contour of sphere and selection of corresponding points of the static pattern from the captured image can be efficiently done by the GUI. By using the corresponding points, calibration of the extrinsic and intrinsic parameters is completed. For 3D reconstruction, images are captured in the same way as the calibration step and then lens distortions are removed. After that, by using the acquired parameters at the calibration step, reconstruction is processed.

VII. EXPERIMENT

Calibration of the active stereo system was conducted using the developed 3D endoscopic system and the GUI. To verify the effectiveness of the calibration method on the intrinsic parameter estimation of the projector, the focal length

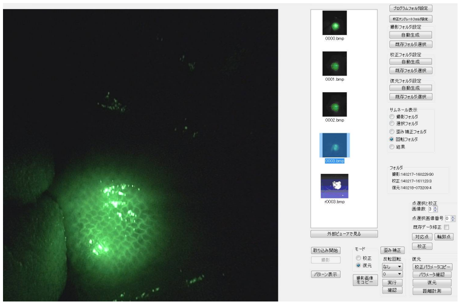
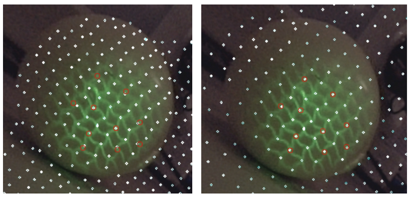


Fig. 6. A sample view of calibration/reconstruction GUI for endoscope images.



(a) (b)

Fig. 7. Calibration result of pattern projector. White points are estimated grid points. (a)Estimation of only intrinsic parameters. (b)Simultaneous estimation of intrinsic and extrinsic parameters.

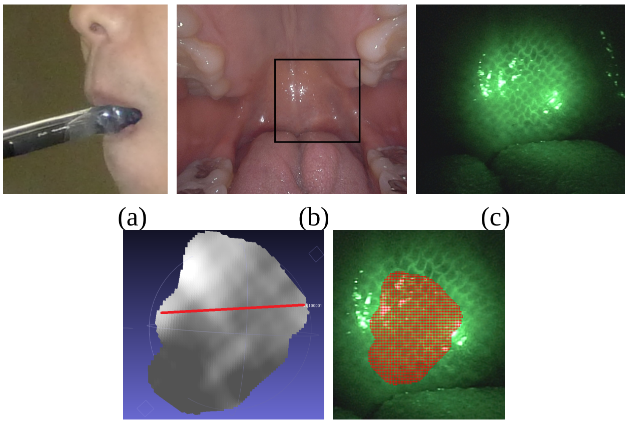
of the projector is deliberately changed by 1.5 times longer than the correct value. Then, the results with reestimation of the intrinsic parameter and without it were compared. Fig. 7 show both the calibration results where the predicted position of the grid points and the actual position detected on the captured image are described on the captured image. From the results, when the intrinsic parameter was reestimated, the predicted positions of intersection points were well fit to the actual positions, whereas some gaps between the predicted and the actual points are observed without reestimation.

Next, the membrane of the soft palate of a human was captured and 3D shape was reconstructed. Fig. 8 shows the result. From the figure, corresponding points which were at the center points of the reconstruction result were analyzed and it is confirmed that correspondences are correct. The measured length of the red line shown in Fig. 8(d) is estimated to be 10.0mm.

Finally, an example of 3D measurement of biological specimen extracted from the stomach of a human by endoscopy operation is shown in Fig. 9. As shown in the figure, we can confirm that the shape was correctly reconstructed.

VIII. CONCLUSION

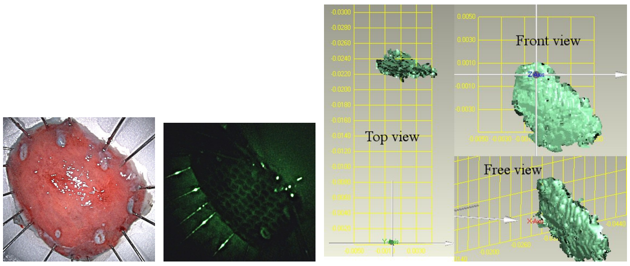
In this paper, we developed a 3D endoscopic system with calibration and reconstruction algorithm and the GUI. In the proposed system, the intrinsic and extrinsic parameters of the pattern projector are simultaneously estimated with the proposed method that uses spherical calibration device. With the system, it is expected to simplify the calibration procedure as well as reconstruction in sites. Furthermore, we developed a graphical user interface that allows users to intuitively calibrate the system and efficiently reconstruct the 3D shape. By using the system, we actually measured the shape of human soft palate and biological specimen.



(a) (b) (c)

(d) (e)

Fig. 8. A sample of reconstruction: (a) the situation of the experiment, (b) the measured part, (c) the image of the soft palate lit by the pattern light, (d) the 3D reconstruction result (length of the red line is 10.0mm), and (e) measured area.



(a) (b) (c)

Fig. 9. A sample of measurement of a specimen extracted from a human stomach: (a) appearance, (b) captured image with pattern projection, and (c) several views of the measurement result.

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