Artif Life Robotics
DOI 10.1007/s10015-016-0311-8

ORIGINAL ARTICLE

An optical projection system with mirrors for laparoscopy

– 3D shape reconstruction for objects based on the reflection light generated by mirrors as the structured light

Mai Sugawara[1,2] · Kaoru Kiyomitsu[1] · Tatsuya Namae[1] · Toshiya Nakaguchi[3] · Norimichi Tsumura[1]

Received: 10 April 2016 / Accepted: 18 August 2016

Abstract We propose an optical projection system aimed at improving laparoscopic surgery based on three-dimensional (3D) measurement that gives an effective information for robotic-assisted surgery and computer-aided surgery. Laparoscopic surgery, which involves the creation of small ports through the patient's body for the laparoscope and surgical instruments, such as clamp, is minimally invasive and has generated a growing interest. There are techniques using the stereo laparoscope to obtain depth information. Active sensing when structured light is added to the laparoscope can reconstruct a 3D shape. However, active sensing that requires projection devices for the structured light leads to an increase in size. Large-sized projection and sensing systems affect surgical procedures. The size of the system is also larger than the size of port for the laparoscope. To remove the obstacle for the surgery, it is important to design downsized systems. For active sensing with the structured light, a small-size projection system is required to use a small port for the laparoscope. Therefore, we built the optical projection system toward downsizing the device to stereoscopic vision of the laparoscope using mirrors, and we show a new shape reconstruction method from its active sensing. Our Experimental results demonstrate the effectiveness of this proposed system and method.

Keywords Active vision · 3D shape reconstruction · Computer-aided surgery · Laparoscopic surgery · Robotic-assisted surgery

This work was presented in part at the 21st International Symposium on Artificial Life and Robotics, Beppu, Oita Japan, January 20–22, 2016.

✉ Norimichi Tsumura
tsumura@faculty.chiba-u.jp

1 Graduate School of Advanced Integration Science, Chiba University, 1-33,Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

2 Faculty of Education, University of Teacher Education Fukuoka, 1-1 Akamabunkyo-machi, Munakata, Fukuoka 811-4192, Japan

3 Center for Frontier Medical Engineering, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

1 Introduction

We propose an optical projection system using mirrors aimed at improving laparoscopic surgery based on three-dimensional (3D) measurement which will give an effective information for robotic-assisted surgery and computer-aided surgery.

1.1 Background

Laparoscopic surgery, which involves the creation of small ports through the patient's body for the laparoscope and surgical instruments, such as clamp. This technique is minimally invasive and has generated a growing interest in the last few decades. Compared with open surgery, surgery done through such minimally invasive techniques leads to lower morbidity, decreased postoperative pain, faster recovery, and a shorter hospital stay.

A conventional laparoscope can produce only two-dimensional (2D) images which do not provide surgeons an actual depth information of the scene. Otherwise, there are techniques using a stereo laparoscope to obtain depth information. The stereo laparoscope has two cameras on its ends. 3D measurement systems of intraperitoneal organs, which are essential to make depth perception using multiple view images and perform robotic surgery,

Published online: 13 September 2016

have been presented in recent research as described follows.

In general, 3D measurement systems are divided into two parts: passive sensors, which measure by simply detected images, and active sensors, which make the use of their light source as an additional displacement information.

1.2 Related research

Stereo vision is used as passive sensing to determine the absolute distance to an object. Stoyanov et al. [1] show that a strategy for 3D depth recovery of the surface structure in robotic-assisted minimally invasive surgery incorporates stereo vision. However, it is known that the measurement accuracy of stereo vision depends on the brightness distribution about the object, and an increase of the density is difficult. We adopt active sensing in this research, because applying passive sensing with stereo vision is impractical for images with less variations in brightness, such as intraperitoneal organs.

Active sensing when structured light is added to the laparoscope can reconstruct the 3D shape.

The reconstruction using active sensing is robust and highly efficient for images with less in brightness, such as those in the abdominal cavity. Time-of-flight, light section, and structured light are known as the examples of active sensing (see Jarvis [2] and Besl [3]).

Active-sensing strategies have been broadly used in laparoscopic vision. Hayashibe et al. [4] show that a laser-scan endoscope using the light-section technique was developed to achieve a 3D visualization of the surgical field in laparoscopy. Hasegawa and Sato [5] devised a technique to realize 3D measurement by combining structured light with laser scanning and the stereo endoscope. In this technique, structured light from projector is guided to the endoscope tip and made to illuminate the object by replacing one of the two cameras embedded in the 3D endoscope. The calculation of the distance value is performed based on the principle of triangulation. The light-section technique also involves calculation as that used for structured light. However, because the light-sectioning uses scanning with slit light and structured light is pattern projection, structured light is faster than the light-section technique. On the one hand, the distance resolution in time-of-flight is low. With these considerations, this research is based on active sensing and structured light. Research on structured light has been conducted, to reconstruct the internal organ shape ([6–9]).

1.3 Problem

However, active sensing that requires projection devices for the structured light leads to an increase in size. Because the system by Hasegawa and Sato requires a laser and scanning mirror, the entire system is thus large. Large-sized projection and sensing systems affect surgical procedures. The size of the system is also larger than the size of the laparoscope port. To remove the obstacle for the surgery, it is important to design downsized systems. For active sensing with structured light, a small-sized projection system is required to the use of small laparoscope ports.

The clinical problem addressed in the present study is how to make the small system for use with the small port in laparoscopic surgery. In this paper, therefore, we propose the optical projection system toward downsizing the device to the stereoscopic vision of the laparoscope using mirrors.

2 System and method

We build the optical projection system to the stereoscopic vision of the laparoscope. In this section, we show a new shape reconstruction method of active sensing of this system.

2.1 Structured light

First, we consider patterns of structured light. A structured light system is based on the projection of various patterns onto the measuring scene which is then viewed by the camera. There are two principal types of coding methods of structured light. It is known as time-multiplexing and spatial neighborhood (see Salvi et al. [10]).

In time-multiplexing, the coordinate value of the projector is coded by multiple structured light images. Within decoding, the coordinate values are determined by all the intensity values of the pixels for each images. To correctly decode the taken images, the time-multiplexing technique is assumed that the object surface is not moved, while patterns are projected on the surface. Otherwise, in spatial neighborhood, all coding schemes tend to be concentrated into one unique pattern. The coordinate value is obtained from a neighborhood of the points around it. The advantage of spatial neighborhood compared with time-multiplexing is that moving surfaces can be measured such strategy permits, in most cases. However, because the codification must be condensed in a unique pattern, the spatial resolution is lower. Moreover, the spatial neighborhood technique assumes a local smoothness of the measuring surface.

Therefore, due to the limitation of the above assumption, because this local smoothness of intraperitoneal organs is not always accomplished, time-multi-plexing is the coding method in our work to perform the measurement tasks.

2.2 Pattern generation

Next, we consider pattern generation. We pay attention to the structured light with the time-multiplexing method based on regularly repeating patterns. In this paper, the reflection light generated by mirrors is used as the structured light. The optical projection systems are designed as a kaleidoscope with a square pillar resembled by the four first-surface mirrors, which can be inserted into the port of the laparoscope. The structured light as diffusion light by a display incidence at one side of the square pillar and image formations are introduced by the convex lens. Moreover, the phase-shift method is used to reconstruct the 3D shape from the structured light shown on the display.

Recently, in the research of structured light, phase-shifting coded with sinusoidal fringe patterns is becoming current interests. Phase-shifting results in high-speed and high-accuracy scanning. Zhang and Huang [11] and Chen et al. [12] developed a 3D shape acquisition system that uses phase-shifting. The system by Zhang and Huang using three images coded with sinusoidal fringe patterns obtained 3D shapes with good accuracy in real time. Because the phase-shift method has the advantage of requiring few numbers of structured light projection to obtain the high accuracy and density of the measurement, and because the light is repeated patterns, we can apply this method to the laparoscopic system.

In this sinusoidal phase-shift method, the coding requires three phase-shifted images. These three projection images of structured light P are as follows:

$$P_1(u) = 255\left\{1 + \cos(2\pi fu/N - 2\pi/3)\right\}, \quad (1)$$

$$P_2(u) = 255\left\{1 + \cos(2\pi fu/N)\right\}, \quad (2)$$

$$P_3(u) = 255\left\{1 + \cos(2\pi fu/N + 2\pi/3)\right\}, \quad (3)$$

where f is the frequency of sinusoidal patterns and, N and u are the resolution and coordination in the horizontal direction of the projector. Intensities of the three images captured by camera I are as follows:

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y) - 2\pi/3\right], \quad (4)$$

$$I_2(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y)\right], \quad (5)$$

$$I_3(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y) + 2\pi/3\right], \quad (6)$$

where $I'(x,y)$ denotes the average intensity and, $I''(x,y)$ denotes the intensity modulation. These values depend on the reflectance ratio of the object. Solving these three equations simultaneously, we obtain the phase $\pi(x,y)$:

$$\phi(x,y) = \arctan\left[\frac{\sqrt{3}\{I_1(x,y) - I_3(x,y)\}}{2I_2(x,y) - I_1(x,y) - I_3(x,y)}\right], \quad (7)$$

and the coordination of the projector u is determined from the phase.

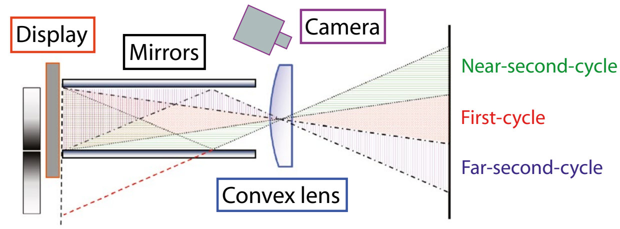

Fig. 1 Optical projection system

2.3 Optical projection system

As discussed above, the reconstruction of 3D shapes using structured light is robust and highly efficient for images with less in brightness, such as images in the abdominal cavity. However, the problem on which this study is based is that projection devices for the structured light leads an increase in size. Therefore, we noted that the repeated projection patterns using the reflection light generated by mirrors achieve the downsizing of the device for pattern projection. Figure 1 illustrates our optical projection system.

The optical projection systems are designed as a kaleidoscope with the square pillar with a base length of 20×10 mm and height of 110 mm by the four first-surface mirrors of which reflection ratio is 94 %. The structured light as diffusion light by a display incidence at one side of that square pillar and image formations are introduced by the convex lens. In Fig. 1, because the red-dashed line means the optical path of once reflected light, the image formation of once reflected light is reversal one above the other pattern of the structured light without reflection. The image formation of more than once reflected light is either a reversed pattern or an erect image in iteration. In Fig. 1 in the right side, the first cycle shows the projection area transmitted directly from the display, the second cycle shows the projection area transmitted indirectly, and near and far show the position in relation to the camera.

Phase-shift methods are used to reconstruct the 3D shape from the structured light shown on the display. The traditional phase-shift method generates multiple cycles of sinusoidal fringe patterns. However, our proposed system generates one cycle and makes periodic cycles with mirrors. Equation (2) produces a symmetric appearance as the same as the traditional phase-shifting, but Eqs. (1) and (3) would not be a symmetric appearance. When the reflected patterns at odd number of times produced from Eqs. (1) to (3) are reversed, the phase could not be calculated from these patterns. This correction algorithm is described in the next subsection.

The intensity at the imaging plane decays with increasing reflection times with mirrors. When k is the reflection

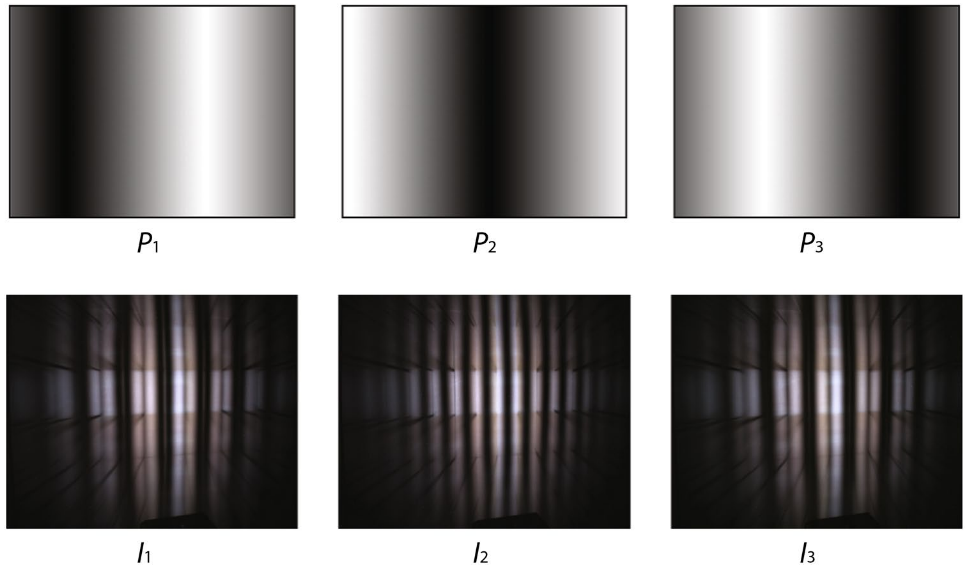

Fig. 2 Generated patterns and formation patterns

times, L is the length of the pillar, and h is the height of the mirrors, we obtain the intensity reflected k times r:

$$r = \frac{\arctan\left[4hL/(4L^2 + \left(4k^2 - 1\right)h^2)\right]}{2\arctan[h/2L]}\rho^k, \tag{8}$$

where ρ denotes the reflection ratio. In our system, $\rho = 94\,\%$, intensity with reflected one time is 93 %, intensity with reflected two times is 86 %, three times is 77 %, and four times is 68 %. The phase could be obtained even when the intensity decreases.

2.4 Correction and reconstruction

Fig. 2 shows sinusoidal patterns P_1, P_2, and P_3 generated on the display and intensity patterns I_1, I_2, and I_3 formed on the projection plane.

Because patterns of P_1 and P_3 would not be the symmetric appearance, patterns I_1 and I_3 are repeated the reversal from the side-to-side pattern and the erect image in iteration. P_1 and P_3 are the phase-shifted P_2 pattern in a different direction. The reversal from the side-to-side pattern of I_1 is the erect image of P_3, and the reversal from the side-to-side pattern of I_3 is the erect image of P_1. When we calculate the phase $\phi(x, y)$ from these projection pattern with Eq. (7), at the area of reversal from side-to-side pattern the numerator switches places with I_1 and I_3 in Eq. (7), and $\arctan\left[-\sin(\phi(x,y))/\cos(\phi(x,y))\right]$ is obtained. Therefore, we consider correction algorithm of this phase $\phi(x, y)$.

We assume that the target object is smooth and parallel between the baseline of camera and optical projection and x-axis of images and direction of sinusoidal wave. It means that the phase is monotonically increasing or decreasing along the x-axis with each areas. In other words, the projection area transmitted directly from the display and transmitted even number reflected pattern, the phase is monotonically increasing, and at the projection area transmitted odd number reflected pattern, the phase is monotonically decreasing. In $\phi(x, y)$, where the gradient of x is negative, the sign of $\sin(\phi(x,y))$ is an inversion and $2\pi - \phi(x,y)$ can be converted to the corrected value. This correction provides the converted phase at the same as the traditional phase-shift method. A continuous 3D phase map is obtained by removing the 2ϕ discontinuity of the image using a phase-unwrapping algorithm described in Ghiglia and Romero [13] and Zhang et al. [14], which is used in this research.

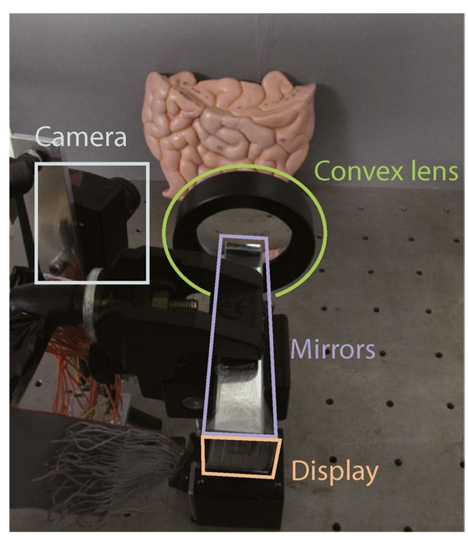

Fig. 3 Experimental setup

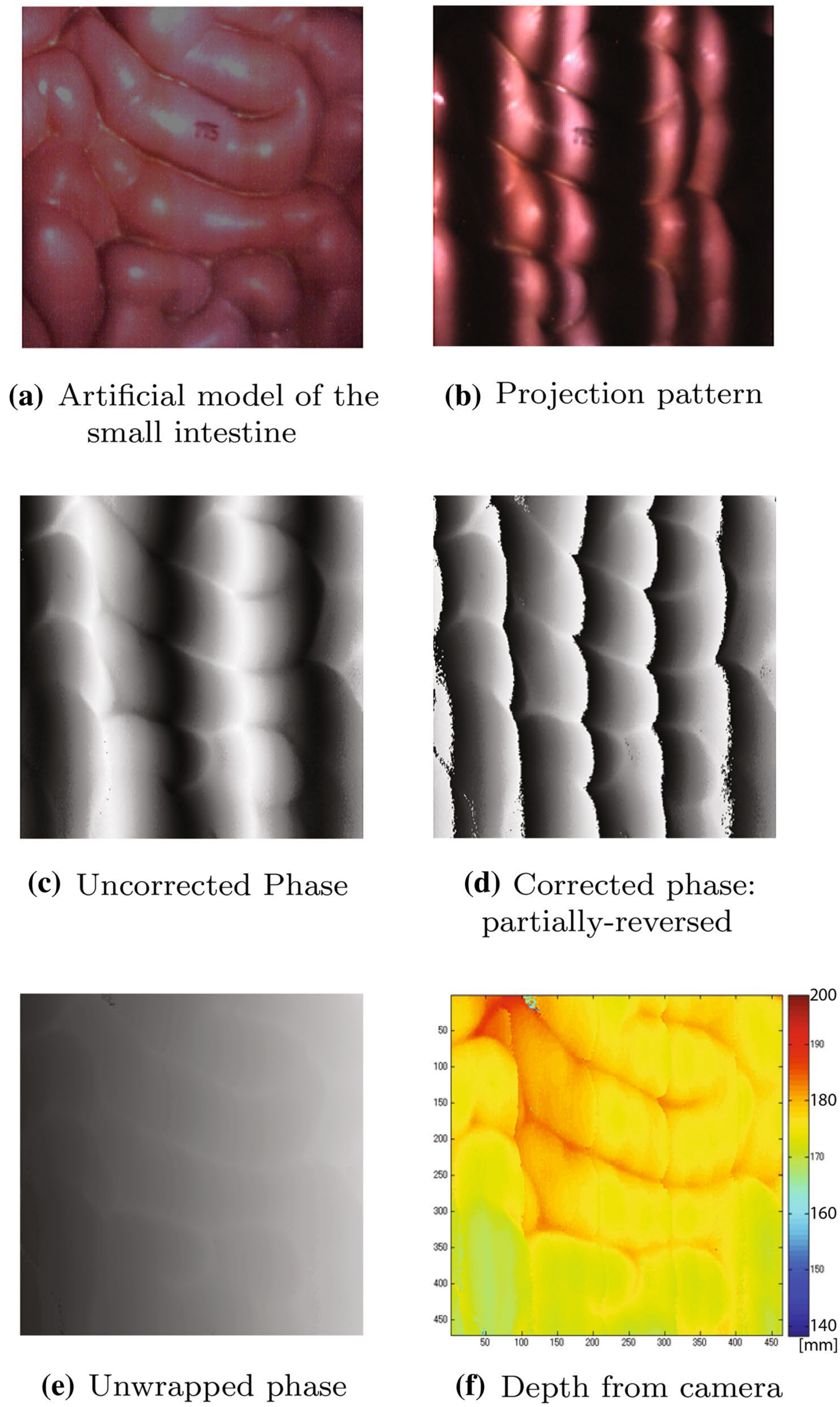

Fig. 4 Original model and reconstruction processing

Next, we describe 3D reconstruction from the phase. 3D coordinate could be obtained as follows:

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \mathbf{P}_c \begin{pmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{pmatrix}, \tag{9}$$

$$\begin{pmatrix} \psi \\ 1 \end{pmatrix} = \mathbf{P}_p \begin{pmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{pmatrix}, \tag{10}$$

where x and y are the image coordinates, and ψ is the unwrapped phase. $\mathbf{P}_c$ is perspective projection 3-by-4 matrix of camera and $\mathbf{P}_p$ are 2-by-4 matrix of projector. Usually, in the structured light projection method, a projector coordinate u is used in the left-hand side of Eq. (10). Otherwise, in the phase-shift method, using the projective transformation $\mathbf{P}_p$ from world coordinates to phase in the right-hand side of Eq. (10), it is possible to replace the left-hand side of the value of the phase and omission of the process for converting the phase value to the projector coordinates.

An already-known shape object can be used for obtaining $\mathbf{P}_c$ and $\mathbf{P}_p$ beforehand. For each pixel of the image x, and y, phase ψ and the world coordinate X_W, Y_W, and Z_W is determined. From these sets, $\mathbf{P}_c$, and $\mathbf{P}_p$ are determined by the least-square method. It is possible to obtain 3D coordinates by solving them.

3 Results

An image of the realization of the proposed system hardware is shown in Fig. 3

An artificial model of the small intestine in Fig. 4a was used as an object.

Figure 4b shows the projection pattern generated with mirrors from the sinusoidal pattern P_1. Sinusoidal patterns P_2 and P_3 were also generated and projected. A set of measured patterns is used obtain the phase $\phi(x, y)$. Figure 4c shows the image of $\phi(x, y)$. Next, in $\phi(x, y)$, where the gradient of x is negative, the phase can be converted to the corrected value. Figure 4d shows the image of the corrected phase. To remove discontinuity of the image, using a phase-unwrapping algorithm to the converted phase, a continuous phase in Fig. 4e is obtained. Finally, 3D coordinates could be determined using Eqs. (9) and (10). 3D coordinates are obtained by converting the coordinate system of the camera. Figure 4f shows the depth from the camera by false color. Even if the area is projected by the structured light with reflection by mirrors, 3D shapes can be obtained accurately using this proposed system.

4 Conclusions

We proposed an optical projection system aimed at improving laparoscopic surgery based on 3D measurement which will give an effective information for robotic-assisted surgery and computer-aided surgery. We have discussed that the reconstruction of 3D shapes using structured light is robust and highly efficient for images with less in brightness, such as images in the abdominal cavity. The problem is that projection devices for the structured light lead to an increase in size. Therefore, we noted that the repeated projection patterns using the reflection light generated by mirrors achieve the downsizing of the device for patten projection. The optical projection systems are designed as a kaleidoscope with the square pillar by the four first-surface mirrors. The structured light as diffusion light by a display incidence at one side of that square pillar and image formations are introduced by the convex lens.

From the results of an experiment, we found out that even if the area is projected by the structured light with reflection by mirrors, 3D shapes can be obtained accurately using this proposed system.

However, the validation of experimental results is still very preliminary. Therefore, we need to improve the experiments as the works natures in the next step of the research.

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