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A Robotic Surgery System (da Vinci) with a Data Fusion System for Navigation Surgery in the Abdominal Region

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ABSTRACT

We describe a data fusion system for the da Vinci robotic surgery system. The data fusion system enables a surgeon to visualize the inner structure of an organ during an operation. The system has two components : an optical three-dimensional (3D) location sensor and a digital video processing system. The optical 3D location sensor measures the da Vinci's laparoscope movement and its direction. The laparoscope's image is captured by the digital video processing system. Using the sensor's data, the system superimposes 3D patient organ models onto the captured image. These processes are executed in real time. After a phantom experiment, we used this system for cholecystectomy and were able to observe the inner structure of a patient's organ stereoscopically during image-guided surgery under the control of a surgeon. (Jikeikai Med J 2003 ; 50 : 19–27)

Key words : data fusion, robotic surgery, image-guided navigation

INTRODUCTION

Robotic surgery systems[1,2] (for example, da Vinci, Intuitive Surgical Inc. ; Zeus, Computer Motion Inc.) were first used for cardiovascular surgery[3–6], then for microsurgery in other regions[7,8]. The systems enabled less invasive surgery and shortened postoperative hospitalization. However, surgeons have difficulty recognizing the thoracoscope's or laparoscope's three-dimensional (3D) location and direction with the narrow field of view provided. We have developed a data fusion system for open surgery and laparoscopic surgery. We applied the system to the da Vinci robotic surgery system. Our data fusion system superimposes 3D images of the internal structures of the patient's organ, such as the location of tumors and vessels, onto the da Vinci's laparoscope image and enables image-guided surgery.

METHODS

The system is composed of a surgeon's console, a patient-side cart, a 3D location sensor, and a graphic workstation (GWS) (Fig. 1). The surgeon's console and the patient-side cart are components of the da Vinci system. The surgeon's console has a stereo viewer and two handles for manipulating surgical tools attached to the patient-side cart's arms. The patient-side cart has three arms that can be controlled from the surgeon's console. Two arms are used for attaching various surgical tools. A stereoscopic laparoscope is attached to the other arm.

The GWS (OCTANE MXE, Silicon Graphics Inc., Mountain View, CA, USA) and the 3D location sensor (Northern Digital, Inc., Waterloo, Ontario, Canada) are components of the data fusion system. The GWS has a digital video processing board that can process two video input and output signals simultaneously. It

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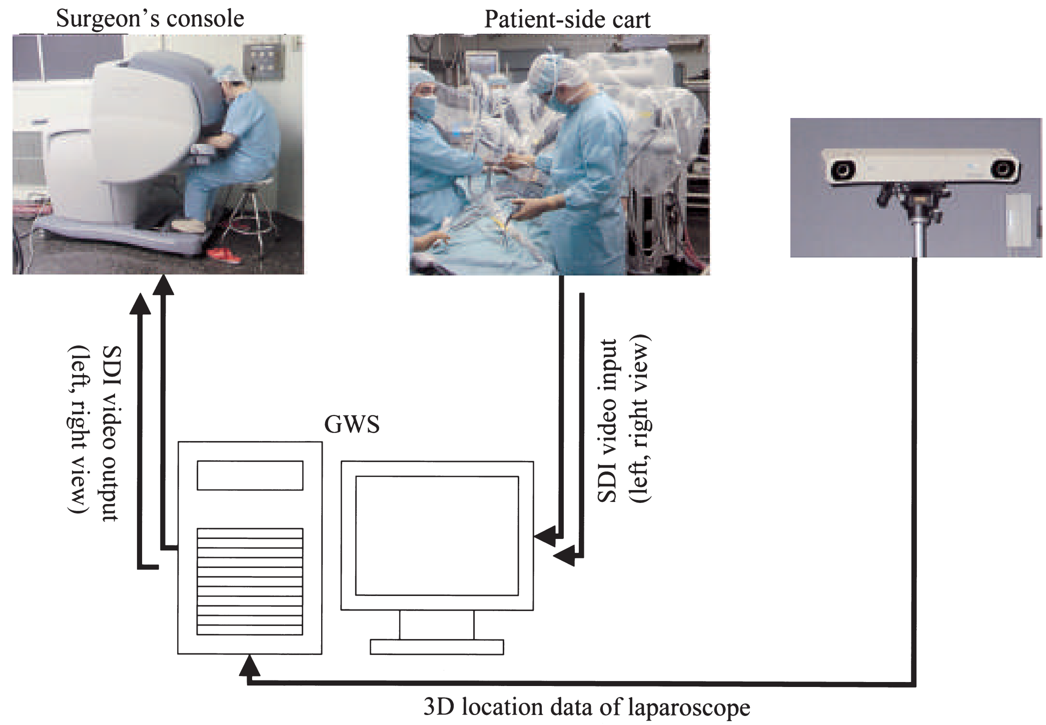

Fig. 1. System outline

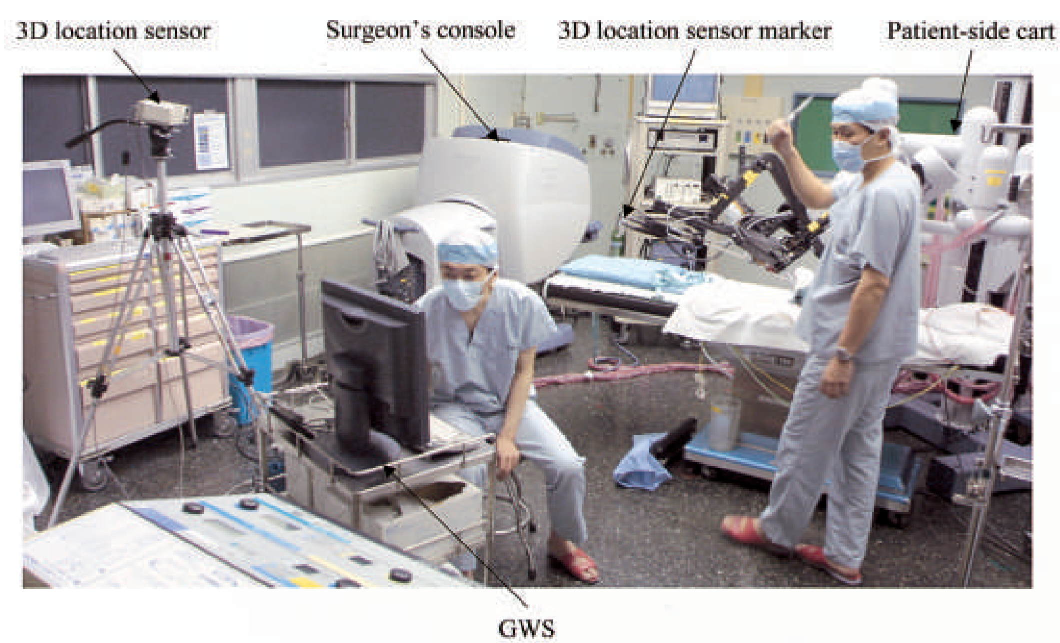

Fig. 2. System displacement in an operating room

reconstructs 3D models of a patient's organs, superimposes the models onto the da Vinci's stereoscopic laparoscope images captured by the video processing board, and outputs the superimposed images to the surgeon's console. The optical 3D location sensor and marker are optical devices that use infrared rays. Therefore, the sensor is not affected by electromagnetic waves produced by electric scalpels or other

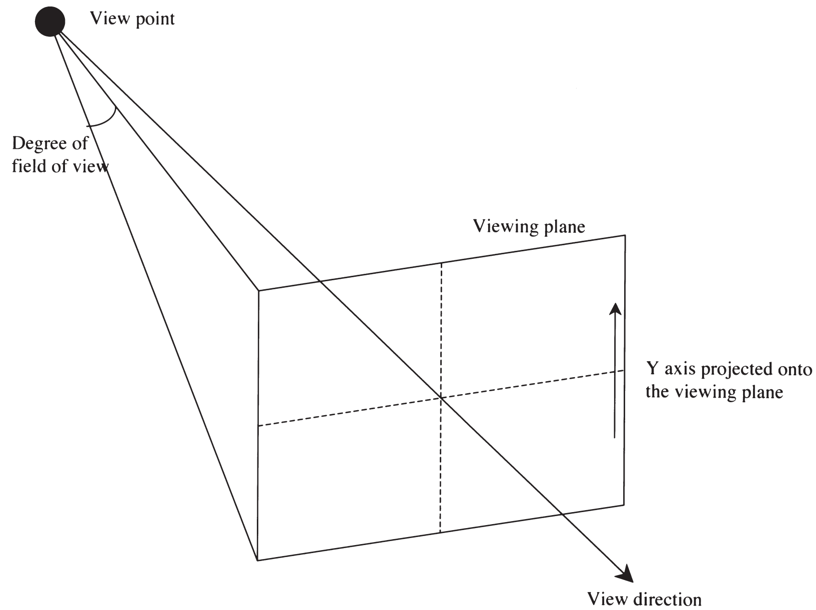

Fig. 3. Laparoscope's optical parameters

devices in an operating room. These devices are used for measuring the laparoscope's direction and location. The marker is fixed on the laparoscope's camera head so as not to interfere with movements of the da Vinci's arm. The disposition of these devices in the operating room is shown in Fig. 2.

Before we use the data fusion system with the da Vinci system, the following procedures are required. In the data fusion system, the coordinate systems of the laparoscope and the 3D patient organ model must be transformed to the coordinate system of the surgical field, and the laparoscope's optical parameters must be determined to project the 3D organ model on a computer display. These parameters are measured with the two following methods.

1. *Measurement of the laparoscope's optical parameters*

In the da Vinci system, the laparoscope must be covered with a sterilized drape during an operation. Therefore, the location sensor marker must be attached to the laparoscope after the da Vinci system has been set up, and this measurement must be simply and immediately performed.

When a 3D organ model is superimposed onto the laparoscope's image, it must be projected onto a computer display with conditions matching the laparoscope's optical specifications. Therefore, a viewing matrix that defines a position in the surgical field coordinate system is required. We assume the laparoscope's optical specification is a perspective projection. The perspective projection is defined by two parameters (degree of field of view and aspect ratio of viewing plane). The viewing matrix is defined by three parameters (view direction, Y axis projected onto viewing plane and view point; Fig. 3). We measure these parameters by using a reference board. The reference board is printed with a square of known size. At two different positions, the reference board image is obtained with the laparoscope, which is fixed to a location sensor marker. Using the two square images and the location sensor's data, we calculate the perspective projection's parameters and the viewing matrix.

After the calculations have been made, the square vertices are transformed to the surgical field coordinate system and superimposed onto the laparoscope image while following the reference board movement. We can check the result by comparing vertices on the laparoscope image and transformed by the calculated parameters.

2. Registration to transform the patient model coordinate system to the surgical field coordinate system

The coordinate system of the 3D patient organ model is not the same as the surgical field coordinate system. Therefore, we must determine a matrix that transforms the patient model's coordinate system to the surgical field coordinate system. On the actual organ, we measured four locations that can easily be identified on the patient model. A pointer attached to the location sensor marker was used to point at these locations. At an actual operation, the pointer was inserted to a patient's abdomen through a trocar. On the GWS display, we specified the same locations that were measured on the actual organ with a mouse. The transformation matrix was calculated with these location data.

To examine the registration method, we used a plaster liver phantom that was modeled from an extracted liver. The 3D computed tomography (CT) dataset of the liver was used to construct organ models. The reconstructed organs included the liver surface, gallbladder, common bile duct, hepatic duct and inferior vena cava. In this experiment, we set the phantom on an operating table. The da Vinci and its arms with the surgical tools were arranged in the same position as in an actual operation. We determined the location sensor and the marker's position on the laparoscope where the location sensor could measure the marker's location continuously during an operation. In this experiment, we also estimated the accuracy of this method and the measurement of a laparoscope's parameters using a rigid cube.

The location sensor data always flickers slightly owing to errors of the sensor, which has an accuracy of 0.35 mm 3D RMS, even if the location sensor marker does not move. When the organ models are superimposed onto the laparoscope image, the flicker makes organ models vibrate slightly. Because the laparoscope's optical characteristics are similar to close-up photography with a conventional camera, a slight change in the location sensor data greatly affects the projection of organ models. Therefore, we processed the sensor data with a moving average method to reduce the flicker. The projection of organ models lags behind the movement of the laparoscope because of this processing. We describe the effect of this delay on the system in the results section.

3. Trial of the system during cholecystectomy

We used the data fusion system with the da Vinci system at cholecystectomy and examined its efficiency. We reconstructed the patient's organ models for this operation from a 3DCT data set. The reconstructed models were the liver surface, gallbladder, common bile duct, and hepatic duct.

The location sensor, reference board, a pointer are made of materials that can be sterilized, because these tools are used in a sterile surgical field. We fixed the location sensor in a position determined with the phantom experiment. After the da Vinci system had been set up, we fixed the location sensor marker on the laparoscope. We measured the laparoscope's optical parameters and registered the organ model and the actual organ. Using these measurements, we superimposed the patient organ models onto the laparoscope image.

To avoid interfering with the surgeon's surgical procedures, we used a video switcher and a foot switch to allow the surgeon to decide whether to use the data fusion system. Also the surgeon was able to change the transparency and color of the organ model to easily distinguish the models from the background laparoscope image.

Results

1. Measurement of the laparoscope's parameters

To measure the laparoscope's parameters, a reference board image was first captured through the laparoscope (Fig. 4a). The captured image was then processed with the GWS. We specified the printed square's vertices on the GWS screen (Fig. 4b). The laparoscope's optical parameters and the viewing matrix were calculated with the vertices. We confirmed the validity of this calculation with a method described in the methods section.

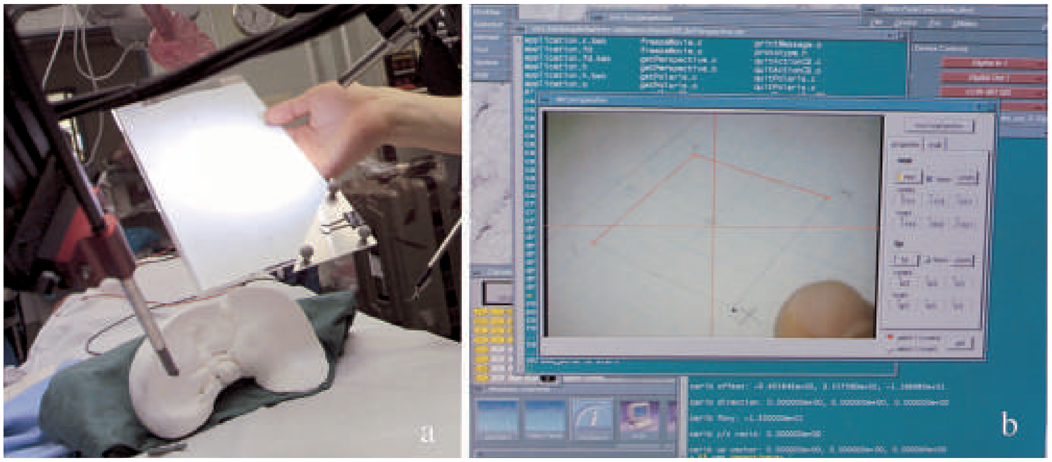

Fig. 4. Measurement of the laparoscope's optical parameters : a : the reference board image is captured through the laparoscope, b : the printed square's vertices are specified on the GWS screen.

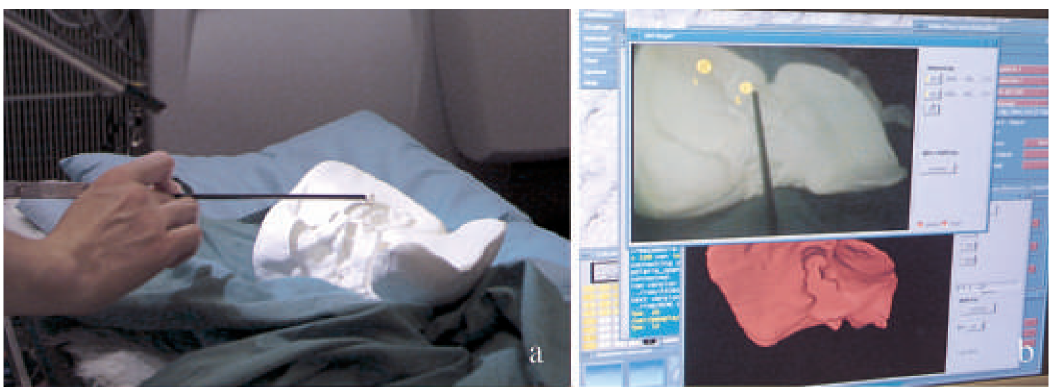

Fig. 5. A scene of the registration. a : The surgeon points at the locations on the liver phantom. b : The registration on the GWS display. The top window shows the result of registration for the liver phantom. The registered locations are shown as yellow spheres. The bottom window is used for registration of the 3D organ model.

2. Experimental results with liver phantom

For registration of the liver phantom, the surgeon pointed to locations on its surface with a pointer attached to the location sensor marker (Fig. 5a). On the GWS, the surgeon specified the same locations that were pointed to on the surface of the liver phantom (Fig. 5b). The locations that were pointed to on the organ model were transformed to the surgical field coordinate system and superimposed onto the laparoscope's image (Fig. 5b : top window). This image was useful to confirm the registered locations and reduce mistakes in registration.

The 3D organ model was superimposed onto the laparoscope's image without vibrations caused by the flicker of the location sensor (Fig. 6). The surgeon was able to watch these images on the da Vinci surgeon's console with a stereoscopic view while controlling the laparoscope and the surgical tools. A moving average method to reduce flicker caused a delay in the organ models' transformation from the laparoscope movement. When the surgeon moved the laparoscope, the superimposed organ models lagged a few frames behind the laparoscope movement. However, the delay was very short and did not affect to the surgeon's procedures.

To estimate the accuracy of the registration and the measurement of the laparoscope's parameters we used a rigid cube of known size. We made a 3D model of the cube and measured the difference in the

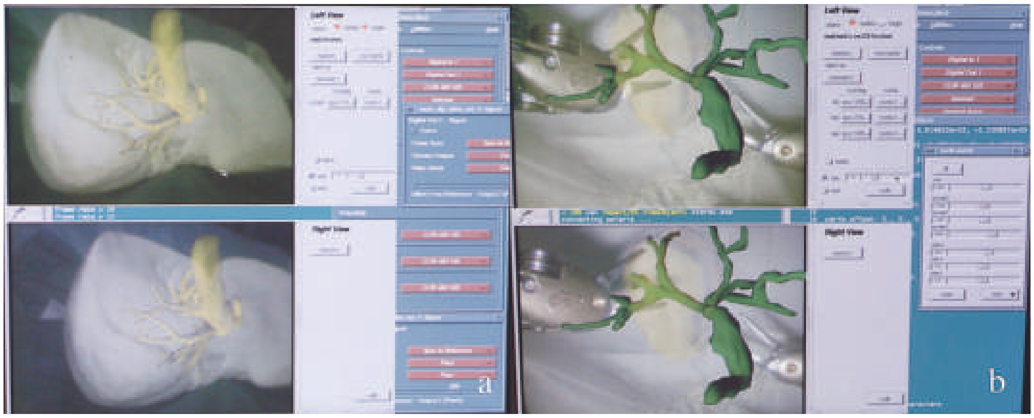

Fig. 6. Superimposing the 3D organ models onto the laparoscope's image. a : The inferior vena cava model is superimposed onto the laparoscope's image. The left eye's view is displayed in the top window, and the right eye's view is displayed in the bottom window. b : The gallbladder, common bile duct, and hepatic duct are superimposed onto the laparoscope's image.

Fig. 7. A scene of registration at cholecystectomy. a : The surgeon points at the locations on the surface of the actual organ using a pointer. b : The surgeon specifies the same locations that are measured on the actual organ.

3D locations of cube's vertices between those measured by the location sensor and those transformed from the cube model's coordinate system to the surgical field coordinate system using the laparoscope's parameters. We measured the locations while changing the position of the laparoscope. The mean difference in location was 3.2 mm.

3. *Results of use at cholecystectomy*

Before using this system at cholecystectomy, we sterilized a location sensor, a reference board, and a pointer that were to used within a sterile surgical field. After we fixed the location sensor and attached the marker to the laparoscope, we measured parameters of the laparoscope. Then using a pointer to which the location sensor marker was attached, the

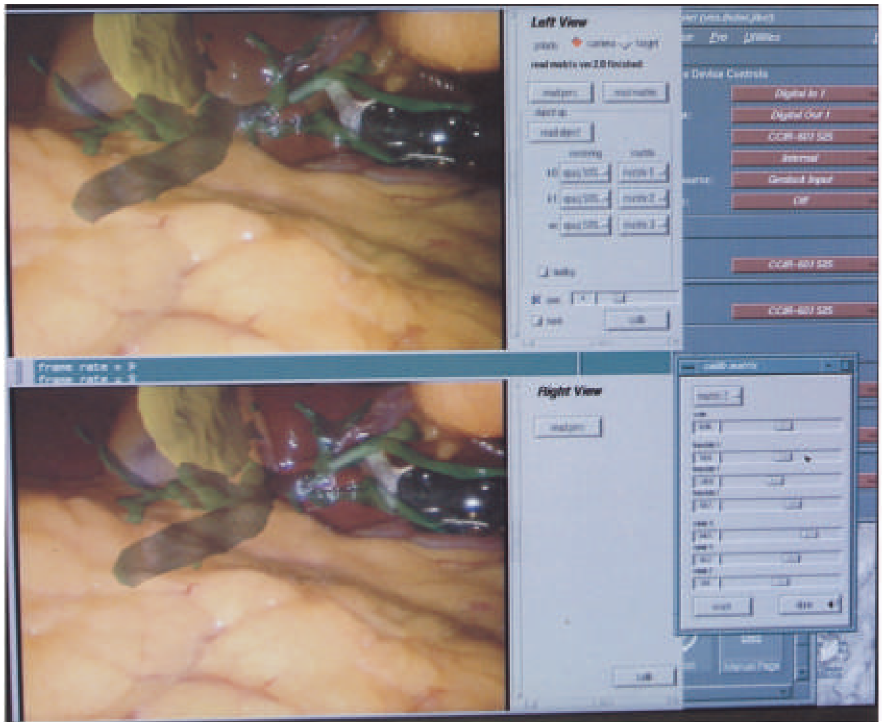

Fig. 8. A superimposed image on the GWS display. The patient's organ models (gallbladder, common bile duct, and hepatic duct) are superimposed onto each eye's surgical field of view.

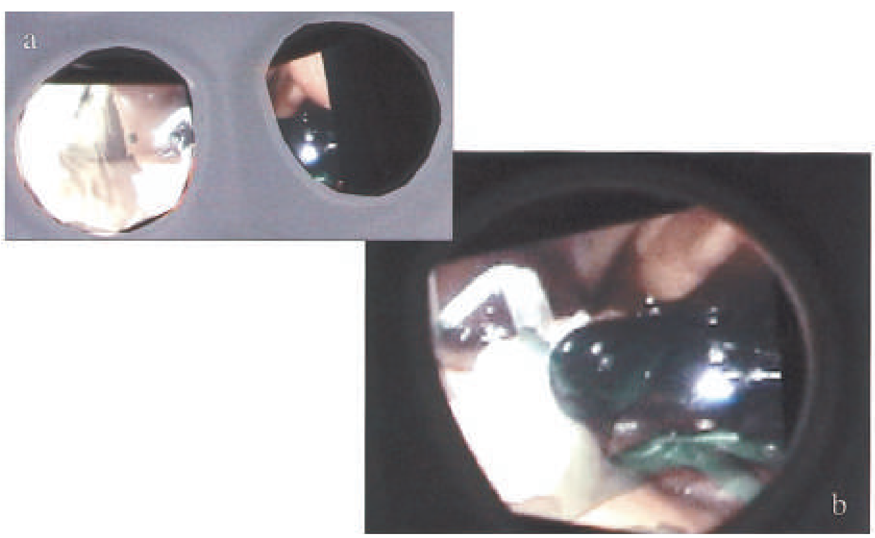

Fig. 9. A scene of the surgeon's console. a : Stereo viewer. b : View from the right eye.

surgeon pointed at the real organ's locations through a trocar (Fig. 7a). The same locations on the patient model were specified on the GWS display by the surgeon's directions (Fig. 7b). The registration took more time than we had anticipated, because the surgeon's pointing movements were restricted by the trocar.

Fig. 8 shows the superimposed images on the GWS display. We were able to visualize the common bile duct and the hepatic duct, which are normally hidden by the liver and fatty tissue in the actual surgical field. At the surgeon's console, the surgeon was able to observe the 3D location of each organ with a stereoscopic view during cholecystectomy (Fig.

9). The surgeon was able to change the transparency and color of the organ models and use the video switcher and the foot switch depending on the situation of the surgical field. In this experiment, the frame rate of this system was 7 to 9 frames per second.

Conclusions

The data fusion system provides the da Vinci robotic surgery system with a stereo image-guided navigating function that follows the laparoscope's movements. This function enables the surgeon to observe an organ's internal structure while looking through the stereo viewer. This function also allows surgeons to concentrate on the surgical procedures and shortens the time of surgery.

Although the system's frame rate was less than 10 frames per second, it did not adversely affect the use of the system during this experiment because this system was only used to confirm the internal structure of organs and the laparoscope did not move. However, we are optimizing the system to improve the frame rate, because we intend to use this system to perform various endoscope procedures. These procedures will require more complex and detailed organ models. Because more computer resources are required to deal with these organ models, the frame rate decreased with the current system. Therefore, we must optimize the system and increase the frame rate for future applications.

The current system requires manual operations for measurement of the laparoscope's parameters and registration of the organ models and actual organs. These manual operations affect the system's accuracy. We are developing a method to measure parameters of a laparoscope without manual operation on a GWS. We are also planning to use a laser-scanning laparoscope[9] to fit a patient's organ model to the acquired organ shape and automate the registration procedure. These methods will improve the system's accuracy and shorten the time to set up the system.

This system's target organs are soft tissue. Organs become deformed after measurement with CT or magnetic resonance and during surgery. This deformation affects the registration of the organ model and the accuracy of superimposing the organ model onto the laparoscope image. Therefore, we must estimate the degree of organ deformation and revise the organ model accordingly[10,11]. We are developing a method to estimate organ deformation[9] to improve the system's accuracy and will validate the system in various laparoscopic procedures.

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