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GPU based real-time surgical navigation system with three-dimensional ultrasound imaging for water-filled laparo-endoscope surgery

Ryo Otsuka, Ikuma Sato, and Ryoichi Nakamura

Abstract—**Presently, a variety of navigation systems are employed in clinical treatments involving neurosurgery, ENT, orthopedic, and head and neck surgery. An ultrasound diagnostic system is used as the navigation system for movable and deformable organs in the abdomen or chest. In this study, we developed a real-time updated 3D ultrasound navigation system that facilitates the high-speed transfer of image data and GPGPU processing for fetal surgery and water-filled laparo-endoscopic surgery (WAFLES). Experimental results showed that our system was able to update every 62 ms. Further, in vivo experimental results showed the ability of our system to guide a surgeon to a target organ during WAFLES in a case where the endoscopic view experienced problems.**

I. INTRODUCTION

Presently, a variety of navigation systems are employed in clinical treatments involving neurosurgery, ENT, orthopedic, and head and neck surgery. An ultrasound diagnostic system is used as the navigation system for movable and deformable organs in the abdomen or chest. The most popular ultrasound navigation system is used for liver cancer. This system calculates the corresponding tomographic image from the preoperative three-dimensional images using two-dimensional ultrasound intraoperative images and navigates the RFA puncture to display ultrasound images and calculate the corresponding tomographic image [1]. In a laparosocopic hepatectomy, the navigation system guides the RFA puncture using ultrasound images of the liver [2]. Other laparoscopic ultrasound navigation systems navigate surgical tools by overlaying the 3D virtual images of vessel models on endoscopic images [3,4].

The problems with these navigation systems for abdominal organs are accuracy issues caused by organ motion and deformation. To solve these problems, intraoperative imaging devices such as ultrasound [4] and MRI [5] are used to acquire precise organ information during navigation surgery. We have proposed and developed a new navigation system using 3D ultrasound image data acquired with a conventional mechanical 3D imaging probe for a fetus. This navigation system can show a wide 3D volume space based on ultrasound image data in real-time. However, it can only be applied to fetal surgery and a percutaneous needle puncture procedure. It cannot be used for laparoscopic surgery because ultrasound imaging is only applicable in the gasless surgical field. Therefore, we propose a new laparoscopic surgical technique called water-filled laparo-endoscopic surgery (WAFLES) [6] for navigation surgery. In WAFLES, we fill the abdominal cavity with saline solution to maintain the surgical field instead of CO_2 gas. We can easily acquire all of the volume data for abdominal organs using a large 3D ultrasound probe percutaneously in WAFLES. We developed the real-time 3D ultrasound navigation system for fetal surgery and WAFLES with parallel computation of the navigation information using a 4-core CPU and low voltage differential signal (LVDS) interface between the navigation PC and ultrasound imaging device. The update rate for the system's navigation information was 2~5 fps [7-8].

In this study, we developed a real-time updated 3D ultrasound navigation system capable of the high-speed transfer of image data and GPGPU processing for fetal surgery and WAFLES.

II. MATERIALS AND METHODS

A. Navigation system

Fig.1 shows the configuration of the 3D ultrasound navigation system. This system consists of the ultrasound diagnosis device (Prosound α7, Hitachi Aloka Medical Ltd.), mechanical 3D ultrasound probe (ASU-1010, Hitachi Aloka Medical Ltd.), optical tracking system (Polaris Vicra, Northern Digital Inc.), and navigation PC (CPU: Xeon W3520, Intel Corp., RAM: 12 GB, GPU: Tesla C2075, NVIDIA Corp., OS: Windows 7 professional 64 Bit, Microsoft). After acquiring 3D ultrasound images and the positions of the surgical instrument and 3D ultrasound probe, the navigation system processes and visualizes the position of the surgical instrument in the ultrasound image space. The Tesla c2075 (448 core) is able to process at 1030 GFLOPS when calculating the coordinate transform and volume rendering, while the Xeon W3520 (4 core) processes only at 61 GFLOPS. Using the GPGPU technology, the processing speed is approximately 17 times faster than parallel computing in a traditional 1~4 core CPU. The raw ultrasound volume data are directly transferred from the memory space of the ultrasound imaging device to the memory space of the navigation PC through a USB2.0 interface. In this system, the ultrasound data are not transferred to the DICOM format and are not stored on the ultrasound device to reduce the reformatting and storage time for the image data.

B. Registration

To navigate surgical tools using this system, we have to develop a registration procedure between the ultrasound imaging space and 3D location information space

R. Otsuka, I. Sato, and R. Nakamura are with the Chiba University, 1-33, Yayoicho, Inage, Chiba, Chiba, 263-8522, Japan (phone:+81-43-290-3934; fax: +81-43-290-3934; e-mail: ryoichin@faculty.chiba-u.jp).

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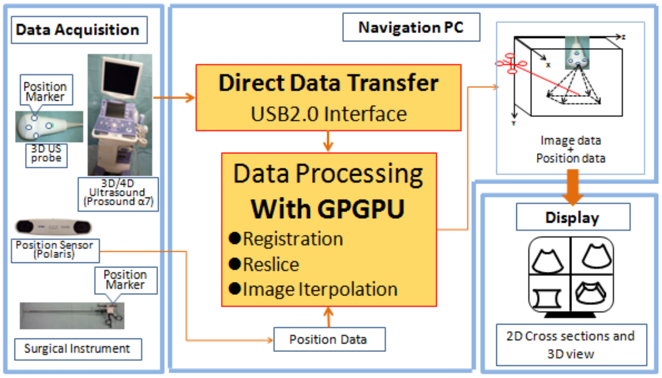


Fig.1 Configuration of 3D ultrasound navigation system.

(Polaris-based space). In this system, the position and orientation of the ultrasound image data are directly determined using the location information from the 3D ultrasound probe. Therefore, the registration procedure can be completed by integrating the coordinate system of the 3D probe and the ultrasound image using the 3D location information measured by the Polaris system.

We previously developed a registration tool for a 3D ultrasound probe (Fig.2) [7-8]. There are 4 stainless steel ball markers (φ2 mm) on the tip of the steel post just under the 3D probe (Fig.2(b)). The positions on these 4 markers are measured in each 3D ultrasound image and in the Polaris system. The marker location information for the 4 stainless steel ball markers and the 3D ultrasound probe detected by a special marker set with 4 passive optical markers (Fig.2(a)) is processed and transformed into location information in the navigation coordinate system. The fiducial registration error (FRE) of this navigation system using this registration tool was about 2.78 mm on average, with a maximum error of 4.51 mm in a previous evaluation [7].

(a) **(b)**

Fig.2 Registration tool for ultrasound image and 3D ultrasound probe.

C. Information processing

The transferred 3D ultrasound image data and 3D positions and orientations of the surgical instrument and ultrasound probe are visualized as navigation information after performing the coordinate transformation by using the registration information. In this system, 3 cross sectional images are rendered using the position information for the tip of the surgical tool. The center point of each cross sectional view shows the position of the tip of the surgical tool (Fig.3). Furthermore, a volume rendering view of the original 3D ultrasound data is displayed on the navigation system.

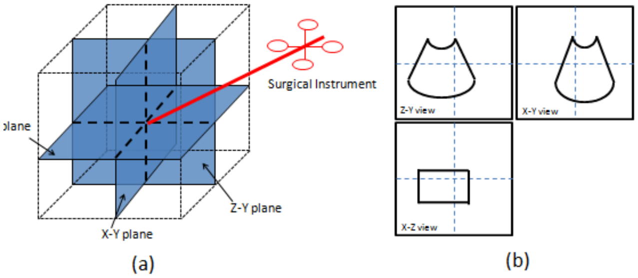


Fig.3 Coordinate system of 3 cross-sectional views using surgical instrument location. (a) Relation between each plane and the surgical instrument. The center of each plane is shifted from the tip of the surgical instrument. (b) Examples of windows.

III. EXPERIMENTS

A. Update speed of navigation information

We evaluated the performance of the "real-time updated" information of the navigation system. We measured the time from the starting point of the data transfer between the ultrasound diagnosis device and navigation PC to the rendering of the navigation image on the navigation PC screen. This includes a) the data transfer time between the ultrasound device and navigation PC, b) the processing time on the GPU and CPU, and c) the rendering time on the display window of the navigation system. We measured these 10 times. The 3D ultrasound volume had the following properties: 204 × 184 pixels, pixel size = 0.95 mm, 26 slices/volume, B-mode scan angle = 60 deg, and 3D mechanical scan angle = 60 deg.

B. In-vivo experiments

In this research, we evaluated the performance of our system in a laparoscopic cholecystectomy, which is one of the most conventional laparosurgeries, using porcine specimens. In these experiments, we used the water-filled laparo-endoscopic surgery (WAFLES) technique [6]. In WAFLES, we fill the abdominal cavity with saline solution to maintain the surgical field instead of CO_2 gas. We can easily acquire all of the volume data for the abdominal organs using a large 3D ultrasound probe percutaneously in WAFLES, but the endoscope view is not clear because of bleeding and other particles in the water condition, in comparison with conventional laparoscopic surgery using CO_2 gas. In this experiment, we evaluated the performance of our navigation system under a difficult WAFLES condition, like one where the endoscope view was of no use because of cloudy water.

IV. RESULT

A. Update speed of navigation information

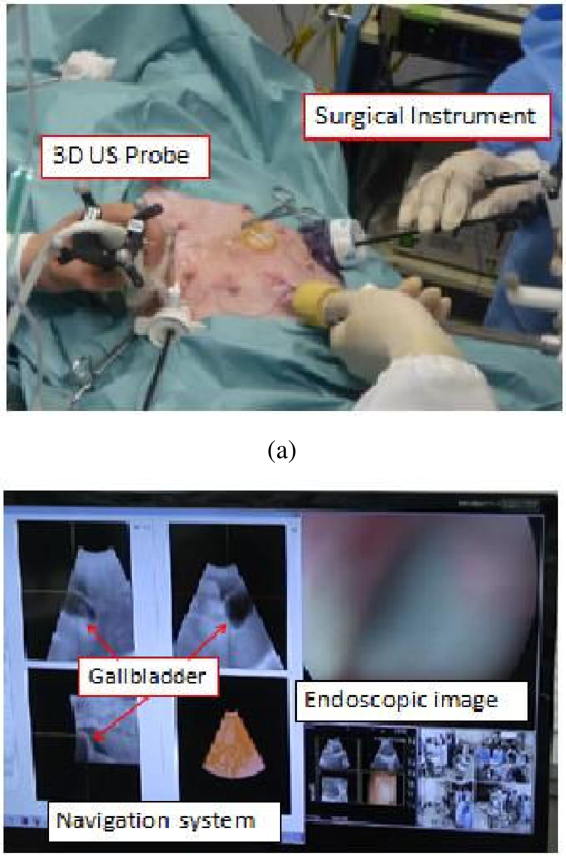
Table 1 shows the result of measuring the update time for the navigation information. It took about 62.1 ms in total, which was shorter than the scanning time for the 3D ultrasound volume (about 158 ms (6.5 volume/s)).

TABLE I. UPDATE TIME FOR NAVIGATION INFORMATION (ms).

Transfer	*Processing*	*Rendering*	*Total*
35.3 ± 0.1	*12.7 ± 0.3*	*14.1 ± 5.1*	*62.1 ± 5.1*

B. In-vivo experiment

Fig.4 shows the surgical field and instruments (a), endoscopic view, and navigation window during an in-vivo experiment. The fiducial registration error (FRE) of the navigation system was 1.01 mm. In this experiment, the saline solution in the abdominal cavity was very cloudy, and the endoscope view was not clear. Our navigation system could visualize the field of view using 3D ultrasound information and could guide the surgical forceps using this information in this situation. The shape and location of the gallbladder was clearly identified by our navigation system, even if it was difficult to find using the endoscope view. In WAFLES, the gallbladder moved frequently because of the buoyancy, but the surgeon could easily track this motion using the real-time 3D navigation information. This system showed strong performances in visualizing, guiding, and tracking movable and deformable organs in the WAFLES environment.



(a)

(b)

Fig.4 (a) Operative field and (b) windows of ultrasound navigation system and endoscopic image.

V. DISCUSSIONS

From the results of the experiments, the update time for the navigation information, including the transfer, computing, and rendering of the data, was about 62.08 ms on average. In this system, the scanning time for a 3D ultrasound image was about 154 ms (6.5 volume/s). Therefore, the update time of the system was fast enough for the real-time updating of the navigation information and was faster than our previous system [5]. However, we have not yet assessed this update ability from the viewpoint of clinical performance. To determine the clinical performance of this system, it is necessary to evaluate it in relation to each treatment, method, target, and demand for accuracy. Although the update time for the navigation information was fast enough, half of it was the data transfer time. We used a USB2.0 interface on this system because of a limitation in the specification of the ultrasound diagnosis system. We can achieve a faster system by using a faster interface for the data transfer between the diagnosis device and navigation, such as a giga-bit Ethernet connection, USB3.0, IR, etc.

In the in-vivo experiment, we could visualize the organs inside the abdomen filled with saline solution using 3D ultrasound images and guide the surgical tools using the volume information. This system is useful for WAFLES such as for a laparoscopic cholecystectomy. This system was very effective in a situation where the saline solution was clouded by bleeding or other difficulties, and the field of the endoscope view was very narrow. In the WAFLES technique, we can acquire wide 3D volume information about the abdomen using a conventional mechanical 3D ultrasound scanner probe because there is no gas in the surgical field, which disturbs ultrasound imaging. WAFLES can allow us to use high-speed scanning of patient information using a large probe. However, there are still many difficulties in a clinical situation, including controlling organ motion under a buoyant condition and maintaining the clarity of the saline solution in the abdomen. In these situations, this navigation system can support the surgeon's view and decisions with its real-time 3D field of view and guidance.

VI. CONCLUSION

We developed a real-time updated navigation system using 3D ultrasound imaging for laparoscopic surgery. We applied a high-speed data transfer interface between an ultrasound imaging device and navigation system using USB2.0, which can directly transfer the 3D volume data from the diagnosis system memory space to the navigation system memory space. We also developed a high-speed computing module for the navigation information using GPGPU technology. The results showed that this navigation system can update the navigation information every 60 ms. Through an in-vivo experiment in a water-filled laparo-endoscopic surgery environment, we clarified the usefulness of this guidance system in a situation where the endoscope view had some problems, such as a cloudy field of view because the water in the abdomen was clouded.

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