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Stereo Display of 3D Ultrasound Images for Surgical Robot Guidance

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Abstract— **The recent advent of real-time 3-D ultrasound (3DUS) imaging enables a variety of surgical procedures to be performed within the beating heart. Implementation of these procedures is hampered by the difficulty of manipulating tissue guided by the distorted, low resolution 3DUS images and the dexterity constraints imposed by the confined intracardiac space. This paper investigates the use of surgical robotics in conjunction with 3DUS to overcome these limitations. In addition, it describes the development of a graphics processor based volume renderer for real-time stereo visualization of the ultrasound data. Stereo displayed 3DUS was compared to 2D-displayed 3DUS and endoscopic guidance with a user study. Five subjects performed *in vitro* surgical tasks using a surgical robot. Results indicate that subjects were able to complete surgical tasks 35% faster with stereo-displayed 3DUS images compared to conventional two dimensional display of 3DUS.**

I. INTRODUCTION

Real-time three-dimensional ultrasound (3DUS) has been demonstrated as a viable tool for guiding surgical procedures [1]. This visualization technique may enable a range of new minimally invasive techniques in cardiac and fetal surgery. For example, beating heart intracardiac procedures are now possible with the use of 3DUS and minimally invasive instruments [2]: ultrasound permits visualization through the opaque blood pool in the heart, and the advent of real-time 3DUS overcomes difficulties with 3D spatial perception in conventional 2D ultrasound [1]. These procedures eliminate the need for a cardiopulminary bypass and its well documented adverse effects, including delay of neural development in children, mechanical damage from inserting tubing into the major vessels, increased stroke risk, and significant decline in acute and chronic cognitive performance [3][4][5].

Initial animal trials highlighted several obstacles to clinical implementation of ultrasound-guided intracardiac surgery [2]. Two such limitations are impaired spatial perception and decreased dexterity, making navigation difficult. Problems with spatial perception are due to the distorted appearance of instruments under 3DUS, including high noise levels, shadowing, and a variety of artifacts, which makes it difficult to visualize 3D instruments and tissue when displayed on a 2D monitor. The decreased dexterity is caused by the necessity of inserting surgical instruments through ports in the heart wall, thereby preventing blood loss and air entry into the heart. These ports limit the range of motion for instruments that are accessing the target site within the heart. A surgical robot is ideally suited for this situation. Recent studies have reported the use of surgical robotics in a variety of surgical procedures [6]. Although there has been considerable work on visual endoscopic guidance, there are no reports of studies using surgical robots with 3DUS guidance. Furthermore, no work has addressed improving the display of 3DUS for surgical robotic procedures.

In this paper we describe the integration of a surgical robot with a 3DUS display. We begin by outlining the new fast volume renderer developed to render the 3DUS volume data on a stereo display. Using real-time data from a 3DUS machine, the renderer displays the information in 3D for a surgeon controlling a surgical robot. The stereo display is tested in tank trials by evaluating subjects' performances guiding a robot through surgical tasks. Subjects performed tasks using conventional endoscopic visualization, stereo display of 3DUS, and 2D display of 3DUS. Results are evaluated in terms of task completion times.

II. METHODS AND MATERIALS

A. Rendering Algorithm

Rendering 3DUS data for visualization challenges the resources of modern personal computers and has generally been reserved for expensive visualization systems. Real-time visualization requires the system to handle and render 40 MB of data every second. However, the consumer 3D graphics industry has driven the computational capacity of consumer-level graphics processing units (GPU) beyond current CPU capacity. This shift has largely been driven by increasing demands by entertainment applications. Therefor, visualization of large volumetric datasets at interactive frame-rates can be attained on consumer-level graphics accelerators [7]. An algorithm implemented on a GPU not only alleviates the processing burden from the CPU, but also meets the high bandwidth requirements of real-time rendering.

The fundamental advantage of programmable GPUs is their ability to execute highly parallelized per-vertex and per-pixel user routines (shaders). While a vertex shader is executed at each polygonal vertex in the scene, a pixel shader is executed at each pixel location of the subsequently rasterized polygon. Our implementation uses pixel shaders to cast rays through the volumetric dataset in a ray-per-pixel fashion (Fig. 1). The intensity (I_{buffer}) and opacity (α_{buffer}) are compounded by sampling the volumetric dataset along the

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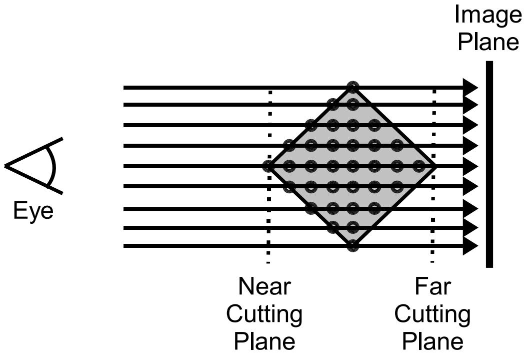

Fig. 1. The dataset is sampled using parallel projection, shown here. Rays are cast in a front-to-back fashion through the 3DUS data, beginning at the near cutting plane and terminating at the far cutting plane.

projection ray as:

$$I_{buffer} = I_{buffer} + (1 - \alpha_{buffer})\alpha_{sample}I_{sample} \quad (1)$$

$$\alpha_{buffer} = \alpha_{buffer} + (1 - \alpha_{buffer})\alpha_{sample} \quad (2)$$

The renderer has been implemented in DirectX 9.0c using the Pixel Shader 3.0 API on a GeForceFX 7800 (nVidia Corp., Santa Clara, CA) with 256MB RAM. The support of hardware loops allows for implementation of the sampling process in a single rendering pass. When rendering typical 3DUS volumetric datasets of size 128x48x204 in full-screen mode (640x480 screen resolution), the renderer maintains highly interactive frame rates of 70 fps and above.

B. System

To address one of the problems with 3DUS guided surgical procedures, the inability to visualize depth, our high performance renderer is used for stereoscopic viewing of the volumes. The high frame rate rendering allows for stereoscopic viewing via consumer-level stereoscopic glasses (eDimensional, West Palm, FL). With stereoscopic viewing, realistic depth perception and spatial interpretation of the 3DUS data is possible. Stereoscopic images are produced by a relatively simple modification of the rendering algorithm described above. Left eye and right eye views are rendered from alternating position and orientation of the camera and synchronized with the glasses shutter rate.

In our implementation, the stereo display of 3DUS was used with a surgical robot. The ultrasound images were produced by a Philips SONOS 7500 3DUS machine (Philips Medical Systems, Andover, MA). The volumes, typically 128x48x204 voxels, are produced at 25Hz and sent over a TCP/IP network to a personal computer running the rendering algorithm. As the data is received from the ultrasound machine, the renderer immediately displays the volume to the monitor positioned at the controls of the surgical robot. As a result, surgeons use the stereo rendered ultrasound data for guiding a surgical procedure as they control the robot.

The surgical robot was a 7 degree-of-freedom Laprotek robot (Endovia Medical, Norwood, MA). The robot is setup in a master-slave tele-manipulation configuration, where movements from the master counsel are mapped to two surgical graspers controlled by the robot. A monitor is positioned in front of the user with the output from the renderer. By wearing the LCD shutterglasses, the stereo 3DUS view is seen by the operator as they control the robot.

Surgical graspers such as those used in this study appear distorted and incomplete in ultrasound. As a result, the graspers were coated with heat shrink tubing and Teflon tape to cover highly acoustically reflective surfaces such as the metal grasper. This treatment greatly reduced the highly specular nature of the metallic graspers and improved their appearance in 3DUS.

C. Evaluation

In order to quantitatively evaluate the surgical robotic system, five test subjects were given two tasks based on those commonly used to train laparoscopic surgeons. These two tasks were selected from among a number of such training tasks proven to correlate to laparoscopic surgical skill [8] [9]. Tasks selected from this validated group were chosen for their emphasis of the importance of depth perception as well as in response to the limiting factors of the ultrasound's imaging characteristics and field of view. The test subjects were required to complete these tasks guided by both 2D-displayed and stereo-displayed 3DUS as well as by a 2D surgical endoscope which provided a bench mark for the comparison of the two ultrasound display methods. Descriptions of the two tasks used follow.

Pegboard: In this task, the test subject picked up a plastic collar sitting around one peg, passed the collar between manipulators and placed the collar around a second peg (Fig. 2A-B). To minimize the effects of any learned muscle motion, the initial and destination pegs for the collar were rotated every trial. Performance was measured by the number of seconds required to complete the task. The pegs were arranged in a triangular pattern on a 5.0cm x 6.5cm acrylic base. The acrylic collar used was 1.3cm x 1.3cm x 1.2cm and had a 1.2cm hole. One trial of the pegboard task consisted of repeating the basic grasp, pass, and replace motion once under one vision system. Subjects performed nine trials, three trials for each of the three vision systems

Rope Pass: The rope pass consisted of test subjects passing a knotted rope five knots from the left to the right manipulator (Fig. 2C-D). Performance was again measured by the number of seconds required to complete the task. A 0.5cm diameter nylon rope with knots on 3.0cm centers was used. The test subject started each test gripping the rope to the left of the first knot with their left manipulator. The process of passing the rope one knot consisted of gripping the rope to the right of the knot currently held by the left manipulator with the right manipulator and then moving the left manipulator to the left of next knot. One trial of the rope pass task consisted of passing the rope five knots under one vision system. Nine trials were performed, three trials for each of the three vision systems

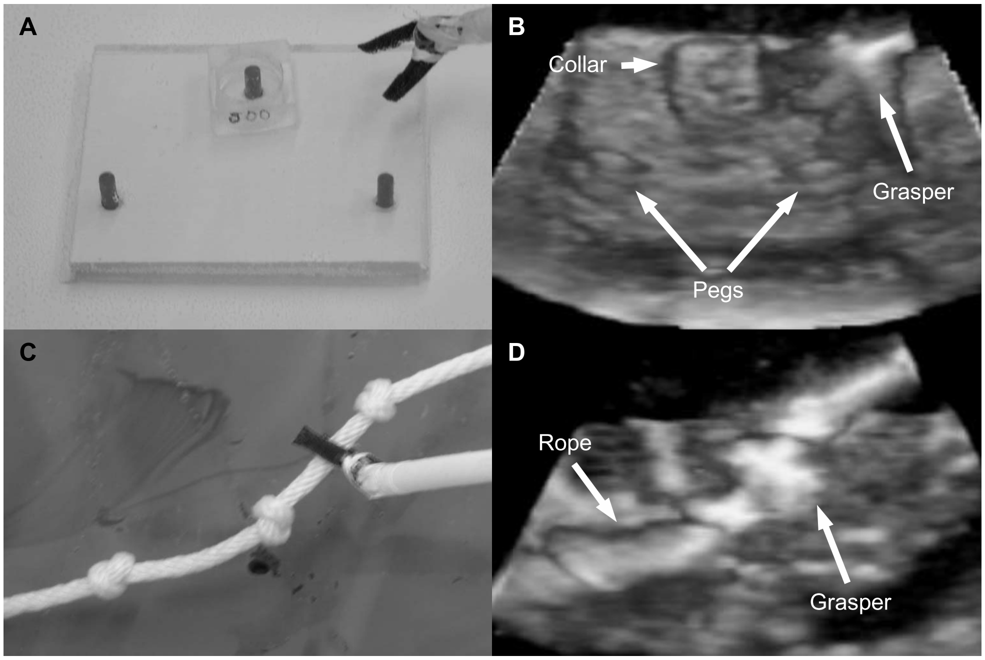

Fig. 2. Image (A) and corresponding 3DUS image (B) of the peg board task. (C) and (D) show the image and 3DUS image of the rope pass.

The test set-up consisted of a 45cm x 60cm x 15cm tank of water over which the Laprotek manipulators, the Phillips ultrasound probe, and a 10mm, 0 degree surgical endoscope were mounted. An absorptive nickel-impregnated rubber mat was placed in the workspace to reduce ultrasound reflections from the bottom of the tank.

The test subjects consisted of college and graduate students ranging in age from 22 to 33. Test subjects' previous experience ranged from completely nonexistent, to research experience with ultrasound imaging, surgical robots, and laparoscopic procedures. None of the test subjects, however, were medical doctors.

Before attempting the actual trials, the test subjects were required to complete a short practice program. This practice brought the subjects to a standard level of ability and limited learning during trials from skewing the collected data. Practice typically took 15 minutes and was divided into two sections. In the first, the test subject manipulated the rope and collar that would be used in the two tasks under the guidance of the endoscopic camera. This familiarized the subject with controlling the Laprotek surgical robot. This continued until subjects were able to demonstrate proficiency by picking up and passing the collar five times and passing the rope five knots. In the second practice section, the subjects completed two trials with each vision system to become familiar with guiding the robot under the trial conditions. These final practice trials were run exactly as the actual data-collecting trials would be and provided the test subject an opportunity to become comfortable with the tasks and testing procedure. This procedure limited training effects during the actual trials, and brought subjects to similar levels of proficiency.

Following the practice program, the test subjects completed the actual testing which consisted of nine trials of the pegboard task followed by nine trials of the rope pass. This provided three trials for each task-vision system combination. Analysis of the completion times of tasks was done with the SPSS statistical analysis software package (Version 13.0 SPSS Inc., Chicago, Il). Statistical significance was determined with a repeated measures ANOVA test with the visual system used as the within subject variable. p values less than 0.05 were considered statistically significant.

III. RESULTS

The results of the experiment show that a stereo display for 3DUS improves the ability of users to control a surgical robot (Fig. 3). For the peg board trial, it took subjects 35±4s (mean ± standard error) to complete the task using the endoscopic camera. Subjects took longer to complete the task using 3DUS, taking 93±14s. However, when the stereo display was used, completion times improved to 60±6s. Although this time could not match the endoscopic performance, it represents a significant 35% improvement in performance over the normal 3DUS view $(F(2,8) = 11.398, p < 0.05)$.

The rope pass trial showed similar results. Subjects completed the rope pass trial with the endoscopic camera in 37±2s. Again, with 3DUS performance degraded, but less severely with the stereo display. Average times for completing the rope pass with the stereo display and a normal display were 57±6s and 86±20s, respectively. Although on average, there was a 34% improvement in performance between stereo and normal 3DUS guidance, it was not a significant one.

On a subjective note, subjects incurred a greater amount of frustration when using the normal 3DUS display as compared to the stereo displayed 3DUS. Most of the subjects stated they preferred using the stereo display or endoscope when compared to the normal 3DUS display.

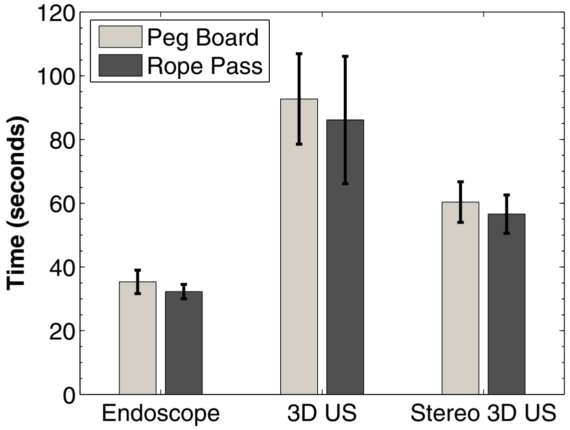

Fig. 3. Average completion times for each task completed under endoscopic, 3DUS, and stereo displayed 3DUS. Error bars show standard error.

IV. DISCUSSION

In this paper we described the integration of a surgical robot with 3DUS for guidance. A stereo display was developed to improve the visualization of the ultrasound data. This system was evaluated with a user study, in which subjects completed simulated surgical tasks with three visual systems: 2D endoscope, 3DUS, and stereo displayed 3DUS.

Results show that subjects were able to complete complex manipulation tasks with a surgical robot under 3DUS guidance. Although the traditional endoscopic view proved to be the best vision system for surgical guidance, tasks were not impossible under 3DUS. In addition, enhancing the 3DUS display with a stereo display improved a users ability to control a surgical robot. On average, subjects were able to complete the task 35% faster with the stereo displayed 3DUS than with normal 3DUS. However, users took about twice as long to complete tasks with stereo 3DUS than with the endoscopic camera. Although not completely reaching the capability of an endoscope, the stereo display did show an improvement over traditional 3DUS display, where users required three times as long.

Statistical analysis, however, only showed a significant improvement between the ultrasound display modes for the peg board task. There was no statistically significant improvement for the rope pass. From trial observations this was due to the repeatable movements involved with the rope pass. Subjects tended to learn a consistent pattern when performing this task, and the stereo display did not significantly improve their performance. However, at points when the subjects' routine was disrupted or the subjects become confused, the stereo display helped them return to their routine. Without stereo, this deviation incurred a large time penalty as subjects struggled to regain orientation. This effect is highlighted by the high standard error (20s) of completion times for the rope pass with normal 3DUS. The use of the stereo diplay had a large effect in the variability in completion times.

With the peg board task, subjects consistently performed better with the stereo displayed 3DUS than the normal 3DUS. This is largely due to a higher complexity task where users were unable to perform a series of repeatable motions, as they were with the rope pass. By varying the start position of the collar, it was difficult for subjects to rely on a set routine of motions to complete the task. As a result, a large amount of visual information was necessary in order to understand the orientation of the graspers, collar, and pegs. The stereo display provided an added dimension of depth that allowed the subject to much more quickly understand the state of the task environment. This is particularly important with the distorted, low resolution 3DUS images where the added depth helps identify objects that otherwise would be indistinguishable on a normal 3DUS display.

The performance improvement seen with the stereo display is consistent with results found with 3D endoscopes [10]. Many studies have demonstrated the improvement of surgical performance when comparing normal 2D endoscopes with 3D endoscopes. However, widespread use of 3D endoscopes has yet to come about. This is largely due to poorer image quality and larger size of 3D endoscopes. With 3D ultrasound, these factors are not present because the same probe and 3DUS volume is used for both stereo and the normal display. As a result, there is no image quality degradation or need for a new larger probe and therefor few foreseeable obstacles to adoption of stereo 3DUS displays.

Through this study, we are just beginning to understand the abilities of 3DUS guided surgical robotics. Future work will evaluate endoscope and robot trained surgeons on the simulated surgical tasks and our system.

V. ACKNOWLEDGMENTS

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