Robot-Assisted Laparoscopic Ultrasound

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Abstract. Novel tools for existing robotic surgical systems present opportunities for exploring improved techniques in minimally invasive surgery. Specifically, intraoperative ultrasonography is a tool that is being used with increased frequency, yet has limitations with existing laparoscopic systems. The purpose of this study was to develop and to evaluate a new ultrasound system with the *da Vinci*® Surgical System (Intuitive Surgical Inc., Sunnyvale CA) for laparoscopic visualization. The system consists of a prototype dexterous laparoscopic ultrasound instrument for use with the *da Vinci* surgical system, an integrated image display, and navigation tools. The system was evaluated by surgeons during pertinent activities, including phantom lesion detection and needle biopsy tasks, as well as in vivo porcine visualization and manipulation tasks. The system was found to be highly dexterous, clinically desirable, and advantageous over traditional laparoscopic systems. This device promises to improve performance of complex minimally-invasive surgical procedures.

1 Introduction

Systems such as Intuitive Surgical's *da Vinci*® combine high dexterity telerobotic control of laparoscopic instruments and high fidelity 3D visualization to give surgeons the ability to manipulate patients' anatomy in a minimally-invasive manner while still preserving many of the advantages of open surgery, including natural hand-eye coordination and improved visual appreciation of the surgical field. In many cases, these systems have been shown to enable surgeons to achieve outcomes equivalent to or better than those of open surgery while still gaining the low morbidity and other advantages of minimally-invasive surgery (MIS) [1, 2]. Although such systems are widely deployed, opportunities exist to improve their capabilities in order to further expand clinical utility and patient safety. In recent years, a number of research groups—including our own—have begun to explore means for more fully exploiting the potential of computers to augment or extend surgeons' capabilities for MIS. These efforts have included preoperative image registration [3, 4], haptic feedback or palpation capabilities [5, 6], "virtual fixtures" to improve accuracy or safety of surgical maneuvers [7-9], and software "toolkits" or environments to promote system integration [10].

Intraoperative ultrasonography (IOUS) is a valuable tool in a wide variety of surgical procedures, including hepatobiliary, urologic, gynecologic, and gastrointestinal surgery.

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Unlike other modalities of imaging, IOUS provides easily attained real-time anatomical information for operative assessment, staging, and real-time guidance for biopsy and ablative procedures. IOUS is being increasingly used with minimally invasive procedures as well. With the loss of tactile information, laparoscopic IOUS provides particular advantages when evaluating solid organs such as the liver or kidney. While the minimally-invasive approach of IOUS offers significant advantages over open ultrasound, constraints exist that limit its efficacy and utility. These include lack of probe mobility, flexibility, maneuverability, and image co-viewing with the endoscopic video. The *da Vinci* platform provides a unique opportunity to develop a useful image-guidance tool for minimally-invasive surgery, yet offer the advantages of dexterity and image quality that could otherwise only be achieved with open surgical approaches.

This paper reports the development of a high dexterity robotic laparoscopic ultrasound (RLUS) tool for the *da Vinci* and its integration into our open-source research software environment, together with initial user experiments. Tasks were created and evaluated based on clinically relevant procedures, including liver scanning and staging, lesion detection, and biopsy.

Hepatic (liver) surgery was the focusing application for this work. Liver cancer surgery is being performed with increasing frequency. Primary liver cancer is the fifth most common malignancy worldwide, accounting for over 500,000 new cases per year [11]. Secondary or metastatic cancer to the liver, originating in the colon, pancreas, breast, lung, among others, is also extremely common. IOUS is a critical component of all liver surgery, used for staging, planning resection, and guiding tumor biopsy and ablation [12]. It is the most accurate method for detecting liver metastases, with accuracy rates above 90 percent [13]. Currently, resection of liver tumors is most commonly performed using open or laparoscopic surgery, with IOUS performed by the direct placement of the ultrasound probe on the liver surface. Liver biopsies and tumor ablations are commonly performed using transcutaneous ultrasound guidance to guide percutaneous needle placement. Although percutaneous approaches have potential advantages of lower morbidity compared to open or laparoscopic surgery, there are also advantages for performing biopsy or ablation in an open laparotomy or laparoscopic environment. Placing the ultrasound probe directly on the liver provides improved imaging compared to transcutaneous ultrasound. Moreover, it allows advanced techniques such as elastography to be employed [14, 15], further improving the surgeon's ability to locate and target structures within this solid organ. Surgical approaches also permit the identification of both hepatic and extrahepatic disease that may not be seen on preoperative imaging, as well as providing better access to difficult-to-reach tumors. In the case of multiple tumors, surgical resection can be combined with ablation. Finally, some studies have suggested that operative surgical ablation may result in better outcomes compared to percutaneous ablation [16].

Several investigators have active programs in robotically-assisted ultrasonography. Fenster, et al. have reported using tracked and robotically-manipulated 2D US probes to produce 3D US images [17]. Several groups have described ultrasound targeting for robotically-assisted needle placement procedures [17-21] while others have developed robotically-manipulated extracorporeal ultrasound systems [22-26]. None of these systems involve laparoscopic ultrasound (LUS) or integrate US into an interventional procedure. Dupont *et al.* have reported work using 3D ultrasound to help guide robotically-manipulated endoscopic instruments, and one experimental system for remote LUS probe manipulation [18] was reported part of a 1998 EU telemedicine initiative. The use of a *da Vinci* robot to manipulate drop-in ultrasound probes has also been reported (e.g., [19]). Many groups have reported use of navigational tracking devices for extracorporeal and laparoscopic ultrasound.

In earlier work [20], we reported on preliminary efforts to produce an integrated IOUS imaging capability for the *da Vinci*, in which we used a simple rigid (i.e., non-articulated) IOUS tool that could be attached to one of the *da Vinci*'s instrument interfaces and manipulated under control of the surgeon's master manipulator. Although experience with this tool was encouraging, it had many limitations. In particular, the lack of a "wrist" made it extremely difficult (in come cases, impossible) for the surgeon to obtain the view desired, especially for tasks such as placing a biopsy needle or ablation probe. Even simply accommodating the probe to the external surface of the organ was difficult to achieve. For these reasons, we undertook development of the more advanced system reported here, in which a wristed (i.e., articulated) IOUS tool is manipulated by the surgeon much as any other *da Vinci* instrument. Our main goals in this study were: i) to demonstrate that such a tool could be integrated and that it could be used effectively by surgeons; and ii) to obtain further feedback to guide further development.

2 Materials and Methods

2.1 System Overview

The schematic shown in Figure 1 illustrates the integration of a prototype articulated RLUS instrument, as well as enhanced image visualization capabilities, with the *da Vinci* surgical robot. The purpose of this system is to allow the surgeon to manipulate a laparoscopic ultrasound probe directly from the *da Vinci*'s surgical console, just as he/she would manipulate a surgical instrument, while observing ultrasound images and associated guidance information within the stereo display of the console.

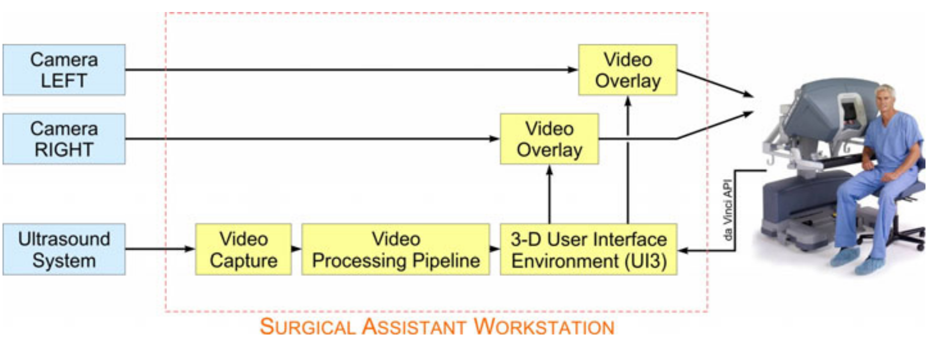

Fig. 1. A high-level system schematic illustrating the use of the Surgical Assistant Workstation (SAW) for video processing, 3-D user interface, and display within the *da Vinci* console. SAW is an open-source medical robotics software framework.

The ultrasound probe, user interface and visualization components are integrated by means of the Surgical Assistant Workstation (SAW) [10]. The SAW is an open-source software framework that has been developed to support medical robotics research. The remainder of this section describes the design and specifications of the RLUS instrument, as well as methods for the visualizing ultrasound images and other guidance information.

2.2 Ultrasound Instrument Design

A prototype *da Vinci* laparoscopic ultrasound instrument was developed based on the 5mm EndoWrist instrument architecture, but scaled to a diameter of 10mm in order to accommodate an off-the-shelf linear laparoscopic transducer (Gore Tetrad, Colorado, U.S.A.). The 5mm wrist is based on a cable-driven multi-link snake architecture that—when scaled to 10mm—is able to accommodate the coaxial cable bundle that is routed through the center of the instrument shaft from the transducer to the system cable interface at the rear of the instrument (shown in Figure 2b).

Fig. 2. (a) A hand-held laparoscopic ultrasound probe (Aloka UST-5536-7.5). (b) The prototype *da Vinci* ultrasound instrument. (c) The ultrasound instrument manipulated by a *da Vinci* robotic manipulator.

The linear transducer contains 128 elements, has a total array length of 46mm, and operates at a center frequency of 7.5MHz. In terms of geometry and imaging performance, the RLUS instrument is similar to standard hand-held laparoscopic probes that are in use today, such as the Aloka UST-5536-7.5 shown in Figure 2a (Aloka America, Connecticut, U.S.A.).

The articulated wrist allows for a range of motion of ±80º in both pitch and yaw angles, thus giving the surgeon six-degree-of-freedom control of the probe, from the master tool manipulators of the surgical console.

2.3 Image Visualization and User Interface

An open-source software framework has been used to display ultrasound images, probe status and guidance information in the stereo display of the *da Vinci* surgical console. B-Mode ultrasound images can be displayed in a variety of ways, including:

1 A split screen display mode in which the surgeon sees the endoscopic and ultrasound views side by side (Figure 3a).
2 A picture-in-picture display mode that insets the ultrasound image into the endoscopic view (Figure 3b). In this configuration, the surgeon is able to select the position and size of the inset image by manipulating the master tool manipulators within the console—this is a user interface feature that is provided by a 3D user interface module implemented within the software library.
3 A "flashlight" display mode in which the ultrasound image is overlaid onto a three dimensional representation of the imaging plane in the stereo view of the console. The effect of this mode is to display the ultrasound image in the plane in which it is physically acquired by the transducer, such that the image is co-located with the view of the tissue that is being imaged in the surgical field. This third display mode is illustrated in Figure 3c. Issues of automatic calibration and image-probe registration were addressed in our prior work with a non-articulated probe [20].

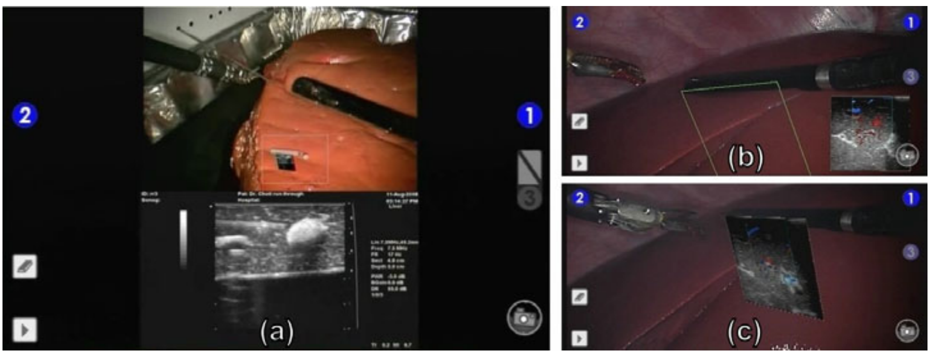

Fig. 3. (a) A split-screen display that shows the endoscopic view and the ultrasound image adjacent to one another in the surgical console. (b) A picture-in-picture view of the ultrasound image. (c) The ultrasound "flashlight" overlay.

In addition to the image overlay, the system displays a graphical representation of the probe, imaging plane, and wrist configuration at the lower margin of the endoscopic view, as shown in Figure 4a. This graphical widget provides the user with cues for orienting the imaging plane of the probe, as well as for avoiding wrist range of motion limits, particularly when the ultrasound probe fills the field of view of the endoscope and the wrist is not visible.

An interesting feature of the *da Vinci* probe is that its location and motion within the surgical field can be tracked by the robotic instrument manipulator. We have implemented two tools that take advantage of this spatial information. The first is a measurement tool that allows the user to measure point-to-point motions of the probe in order to estimate the perpendicular distance between two image planes. This can be used to estimate the out-of-plane width of a lesion without having to re-orient the probe.

A second tool allows the user to map the relative locations of features of interest within the surgical field, such as the locations of lesions or anatomical landmarks. The map shows the current location and orientation of the probe as a graphical “cursor”, as well as the locations of markers that have been dropped as “bread crumbs” during the course of a procedure. This is shown in Figure 4b. By moving the probe cursor to align with the markers, the user is able to return to and re-examine ultrasound views of interest.

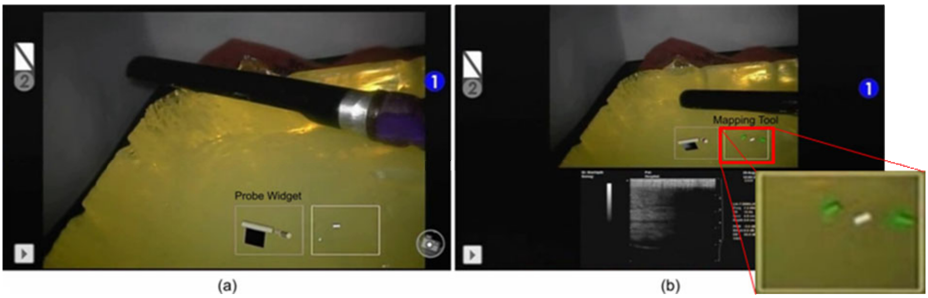

Fig. 4. (a) The graphical probe widget indicates the transducer and image plane orientation as well as wrist configuration. (b) A mapping tool indicates the current probe position and orientation (white cursor), as well as “bread crumbs” (green markers).

2.4 User Studies

A user study was conducted in order to evaluate the performance of the robotic ultrasound probe, as well as to compare its capabilities against a standard hand-held laparoscopic probe. This section describes these experiments and preliminary results.

Each task discussed below was completed with both the robotic system described above, and a standard laparoscopic ultrasound instrument (Aloka UST-5536-7.5, as shown in Figure 2a). Surgeons experienced with laparoscopy and IOUS were recruited to participate in the user study, following protocol approval by the Johns Hopkins University Institutional Review Board. A total of ten subjects participated in the study; seven completed the full protocol, while three subjects completed only the lesion finding or biopsy tasks. All subjects’ results and questionnaire responses were used where appropriate. The subjects came from a wide variety of backgrounds and specialties, although we focused on subjects with some laparoscopic, robotic and ultrasound experience. Figure 5 shows the experience of the subjects in each of these main

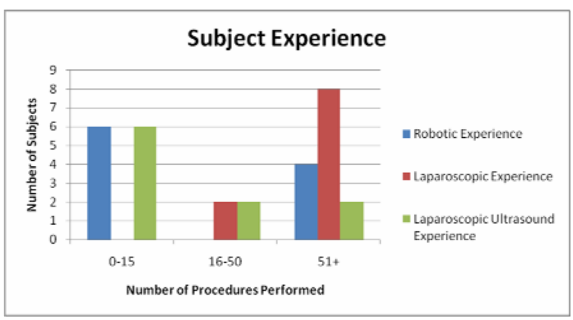

Fig. 5. The experience levels of the 10 study subjects. Each subject reported their experience as the number of procedures they had performed in several relevant areas.

areas. All subjects were scored equally, despite their level of experience in a particular area.

Specific tasks were designed based on surgical relevance and difficulty with traditional laparoscopic techniques. Both *in vivo* and *ex vivo* models were implemented, using the liver as the target organ for study. These tasks included: (1) liver surface manipulation and imaging volume capability, (2) detection and imaging quality of intrahepatic structures, (3) lesion detection and (4) needle biopsy guidance. The time to complete each task was recorded, in addition to other specific measures related to the successful completion. A short period of practice was allowed for each task. The task was explained in detail before beginning and all questions from the subjects were answered at this time. The order of the tasks was randomized in order to minimize learning effects. Upon completion of the tasks, a questionnaire was administered to each subject to query their satisfaction and clinical usefulness of the system. The results from this survey are shown in Figure 6.

The first two tasks mimic exploration of a solid organ, as might be done during the assessment of liver during hepatic surgery. First, the subjects were asked to scan of the anterior surface of an *in vivo* porcine liver, contacting as much of the liver surface and scanning as much of the liver volume as possible. Videos were recorded and blindly scored after completion, based on the amount of surface reached and the quality and consistency of the ultrasound image produced. The subjects were then asked to identify and image specific structures within the liver: gallbladder, portal veins, hepatic veins, and the inferior vena cava. They were asked to capture US images in both transverse and sagittal planes. Video and still images were then blindly scored based on the quality of ultrasound images and the ability of the surgeon to manipulate the probe into the proper orientation. Each image was scored on a scale from 1-4, 4 being outstanding and 1 being poor. A total of 44 points were awarded for the *in vivo* tasks. Subjects were scored from 1-4 on their ability to scan as much of the liver surface as possible. Points were awarded based on the percentage of each liver lobe that was covered. Each of the eight images of the four anatomical features was worth up to 4 points and additional scores were given based on image quality and the subjects' ability to manipulate the probe.

The third task mimicked lesion detection in a solid organ. For this, phantoms were constructed from polyvinyl chloride (PVC) plastic, similar to material described in [21]. Both hyper- and hypo-echoic lesions were created using different proportions of an acoustic scattering material (glass microspheres). These phantoms measured approximately 20cm × 10cm × 5cm. Lesions varied in conspicuity (echogenicity), depth, and size (5-15mm diameter). All lesions were spheroid in shape. Subjects were provided a phantom containing 1-8 lesions, the actual number being unknown to them. They were asked to identify and measure all lesions as accurately and rapidly as possible and declare when completed. The percentage of lesions correctly identified was recorded and scored, as well as the overall measurement accuracy (in estimating lesion volume). The score for this task was a combination of the percentage of lesions found within the phantom, the total percent volume error in the measurement of the lesions, and the subjects' confidence that they had found all of the possible lesions. Each of these scoring metrics was given a total of 12 points, so that the maximum score achievable in this task was 36 points.

The fourth task determined the capability of the subject to perform accurate ultrasound-guided needle core biopsy using the RLUS system. For these studies, phantoms were created from *ex vivo* bovine liver. Target *1*cm lesions were made using fast-setting dental alginate polymer and inserted at least *3*cm within the liver parenchyma. The alginate material polymerizes as a semi-firm material similar in consistency to human liver and can be biopsied using a needle core biopsy device. In addition, the polymerized material is white in color, enabling easy identification of a successful biopsy. The liver phantom was placed within an opaque torso model and subjects were allowed to practice and shown the location and US appearance of the target. They were then asked to robotically guide the biopsy needle to the target lesion using the RLUS system. The biopsy device was stabilized and deployed by an assistant from the outside when told by the subject. The success of the task was determined by the presence of the white polymer material in the extracted biopsy core. The number of times the subject punctured the surface of the liver was recorded. This is important in a clinical environment where excessive bleeding and tissue damage can be caused by repeated punctures through the surface of the organ. An overall score was determined as a combination of the positive biopsies, the number of liver punctures and the time that was required to acquire the biopsy, yielding a maximum possible score of 36 points for this task.

Average and standard deviation for each task was calculated and scoring scale was used to in order to provide each section of the task a weighted point value. All points are combined in order to produce a final score for each subject. In order to gain insight into each task that was completed, each mean and standard deviation are displayed independently and grouped by task.

Scores for each task were determined either by the evaluation of video, by comparing the values reported by the subject with known values and configurations of a phantom, or by visual confirmation. These scores were then summed for each task and summed for the entire experiment. These results are shown as percents of the maximum score in Table 1.

The robotic portion of this experiment also incorporated the image visualizations and user interfaced discussed in the previous section. To simplify the experiments and avoid confusing the subjects, the interface additions were displayed when it was believed to be most useful to the subjects. The graphical representation of the ultrasound tool, as seen in Figure 3a and Figure 4 was used during all tasks. The mapping tool (Figure 4) and the measuring tool were used during the lesion finding task. This allowed the subjects to determine if a lesion had been previously identified, and allowed an accurate measurement of out of plane motion.

The user interface illustrated in Figure 3a was used to facilitate the study described in the remainder of this paper. Early surgeon feedback indicated some discomfort with the “flashlight” display mode shown in Figure 3c, primarily due to regions of interest within the surgical field being obscured from view by the ultrasound image overlay. Surgeons much preferred a split screen or picture-in-picture display, with the probe widget and mapping feature inset for guidance. A simple manual calibration of the ultrasound-to-image transform was used to render the probe widget, as this tool was intended to indicate approximate probe orientation and wrist configuration only. While only an approximate ultrasound image calibration was required to evaluate the feasibility of the "flashlight" image overlay, one can implement a more accurate automatic calibration similar to that described in [20].

2.5 Results

Although the study subjects came from varied backgrounds and had a wide range of experience levels, experience level did not correlate to a significant change in the final score of the subjects. Table 1 shows the mean and standard deviation of the scores for each of the tasks and subtasks. The scores are shown as a percentage of the total attainable point score. The mean combined score for *in vivo* tasks completed with the robotic instrument was 80.2% ± 7.3%.

Table 1. Results from a selection of experiment tasks, as well as combined scores. All scores are shown as a percentage of the total possible points available, except in the case of the average number of punctures during biopsy. The weighting of each task represents the total possible points that are available for that particular task or subtask. Please note that not every subtask is listed in the table.

Task	*da Vinci* Mean ±σ [%]	Weighting	Scoring Method
Lesions Found	72±16.4	12	Compared to known phantom
Lesion Volume Error	27.8±11.3	12	Compared to known phantom
Confidence in Lesion Identification	72.5±15.3	12	Subject questionnaire
Overall Lesion Task Score	62.5±16.2	36	Weighted average of lesion scores
Positive Biopsy	50±35.6	12	Visual confirmation of pseudo
Average number of Punctures	2.66±2.1	12	Scored from video
Overall Biopsy task Score	56.6±20.35	36	Weighted average of biopsy scores
Liver Surface exploration	84.5 ± 8.9	12	Expert evaluation
Anatomy Identification	76.2±14.4	24	Expert evaluation
Tool Manipulation	78.6 ± 9.4	4	Expert evaluation
Combined In vivo task score	80.2 ± 7.3	44	Weighted average of expert scores
Total Combined score	**64.0 ± 13.1**	**116**	**Weighted average of all scores**

During the lesion finding task, each subject was presented with a phantom that included anywhere from 1 – 8 lesions. The average percentage of the number of lesions found with the *da Vinci* ultrasound instrument was 72%. The total error for this task was relatively low at about 30% and the overall score of this task was 62.5%.

The biopsy task presented the greatest challenge to all subjects and the results are shown in Table 1. Most of the subjects had very little experience in this area, and this was the most difficult of the 3 tasks. Out of a total of 3 biopsy attempts, the subjects were successful in, on average, 50% of the attempts with the robotic tools. A positive biopsy was verified visually by examining the core of tissue from the biopsy needle. The maximum number of punctures varied widely, from a maximum of 10 in one case to a minimum of a single puncture. There was no obvious correlation between the number of punctures and a successful outcome. All the subjects were combined and the mean and standard deviation are reported in Table 1.

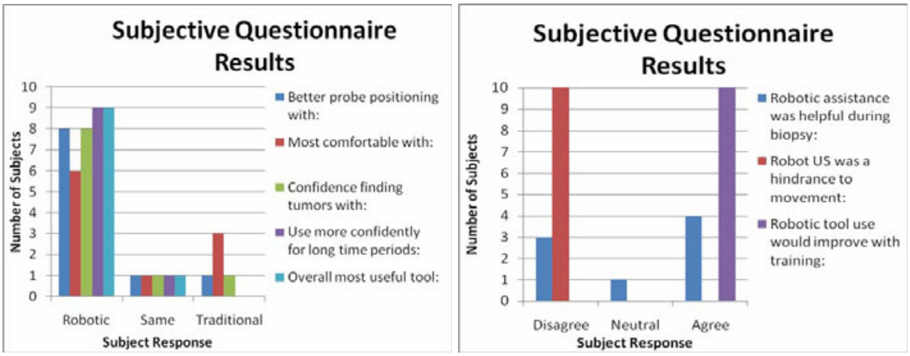

Fig. 6. The results from the subjective questionnaire, which asked subjects to agree or disagree with several statements, and compare the robotic ultrasound instrument against their experience with traditional hand-held laparoscopic probes.

A selection of results from the subjective questionnaires is presented in Figure 6. The subjective questions allowed us to assess how the subjects felt about the tasks and tools and compare there experiences during the study to their experiences with traditional handheld laparoscopic ultrasound tools. Most notable among the responses was to the question: "Which instrument did you find most useful over all?" In this case, 9 of the 10 subjects replied that the robotic instrument was most useful. The one subject that replied that they felt both tools were equally useful was only able to complete the lesion finding task. Every subject also disagreed that the robotic tool was a hindrance to their freedom of motion.

Many of the subjects expressed their enthusiasm for the user interface additions. They appreciated the additional information that was provided to them, even if they did not take full advantage of that information. The measurement tool and the mapping tool were used extensively by the subjects during the lesion identification task. This interface was used to help with lesion dimension measurements, and to avoid measuring the same lesion multiple times. The probe representation (Figure 4a) was most beneficial during the *in vivo* anatomy identification and the simulated biopsy. In both of these tasks, it was necessary to know, with some accuracy, in which direction the US beam was facing. In the first case, it was used to determine to the location of liver structures, and in the second case to align the imaging plane with the incoming needle.

3 Discussion

The robotic laparoscopic ultrasound system presented here has the potential to overcome many of the limitations found with our current technologies. We have shown that high-quality operative ultrasound imaging can be achieved using the minimally-invasive *da Vinci* robotic platform. These studies demonstrate the RLUS probe to be capable of covering a large amount of the liver surface, generating imaging comparable to that of open IOUS. The high level of dexterity and image quality documented in these studies validate the potential usefulness of our RLUS system for improving the performance of complex surgical tasks though a minimally invasive approach. Interestingly, we found that the additional features that were integrated into the system markedly contributed to user satisfaction. These included a variety of image display options (e.g., split-screen, picture-in-picture, flashlight overlay), measurement tools, probe status widget, and a landmark mapping capability.

The subjects were able to complete all the tasks to a satisfactory level, and their overall performance indicates that the system provides an effective environment for IOUS even in its current prototypical state. Qualitatively, the subjects' feedback, as drawn from responses to the study questionnaire, was very positive, both with respect to the effectiveness of the articulated *da Vinci* IOUS tool and in comparison with traditional hand-held articulated laparoscopic probe. A detailed quantitative comparison of surgeon performance between the *da Vinci* IOUS tool and a hand-held probe is beyond the scope of this paper, and will be taken in future work. Despite the small sample size and the need for rigorous statistical analyses, however, preliminary indications are that performance with the *da Vinci* IOUS tool is at least comparable to that with traditional instruments. Further, one significant advantage of the integrated *da Vinci* approach is that the surgeon has much better interactive control over the probe to obtain the image that he or she wants while doing the surgery, rather than having to coordinate with an assistant to control the imaging at the patient side.

The experience of the subjects participating in this study varied widely, from those who had almost no robotic experience to those who were very experienced robotic surgeons. Their experience with porcine anatomy and the general use of laparoscopic ultrasound also varied significantly. Nevertheless, the results of the subjective questionnaire are interesting when subject experience is taken into consideration. Whereas most subjects had more traditional laparoscopic experience than robotic, they were still likely to agree that they were better able to position the probe, and that they were more confident and less fatigued when using the robotic ultrasound instrument. In all cases, the subjects agreed that they believed their performance would improve with additional training time.

4 Conclusions and Future Work

This paper has reported the development and initial user evaluation of a dexterous laparoscopic ultrasound tool and supporting augmented reality software for the *da Vinci* surgical robot. This combination provides surgeons with an effective and natural means of using intraoperative LUS, providing much of the "feel" of open intraoperative ultrasound imaging within a *da Vinci* telerobotic environment. Our main goals in developing this system were to gain experience with an articulated IOUS tool for the *da Vinci,* to determine whether such a system could indeed provide an effective IOUS capability for a surgeon, and to obtain feedback for future study. Our initial experiences with the system are encouraging, and the response from surgeon users has been positive**.** The qualitative feedback from our very small preliminary study indicates that the system offers significant advantages in probe positioning and confidence in finding tumors, compared to subjects' experience with traditional freehand articulated LUS probes. A careful statistical analysis of relative quantitative task performance measures is planned for future work.

Although our initial phantom and *in vivo* studies used liver surgery as a focusing application, the system is readily applicable to other surgical procedures, including kidney and prostate surgery, pancreatectomy, and gynecologic procedures. One near-term target is laparoscopic partial nephrectomies. Concurrently, we are beginning to explore enhancements to our software environment to further exploit the potential of *da Vinci* LUS. Topics include: incorporation of "virtual fixtures" to assist surgeons in acquiring LUS images and 3-D volumes; palpation behaviors for assisting in acquisition of LUS elastography images; registration of LUS B-mode and elastography images to preoperative cross-sectional imaging and surgical plans; 3D augmented reality displays of this information within the *da Vinci* console; and improved tools and software virtual fixtures for assisting in LUS-guided biopsies and other needle placement procedures. Further study of the user interface and display methods illustrated in Figure 3 would also be interesting. In particular, a follow-on comparative study of the ultrasound image display modes, using the same tasks described in the present study, may provide guidance for further taking advantage of the robotic system for enhanced image guidance and navigation.

Application of IOUS to the *da Vinci* system provides many additional benefits above and beyond that of even open surgical imaging. The high quality stereo endoscopic visualization and control of secondary grasping and manipulating tools provided with robot further improves IOUS. Moreover, integration of IOUS into this robotic platform will allow for future improvements in the system, including robot-assisted integrated tool guidance and image registration. In order to continue expanding the indications and improving outcomes of robotic surgery, development of image-guidance tools such as these are important. Systems such as these will allow for expanded use of minimally invasive techniques for complex surgical procedures not otherwise amenable to this approach. Moreover, developments such as these have the potential to improve patient safety and reduce health care costs through more cost-effective use of robotic systems.

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