3D Ultrasound Imaging in Image-Guided Intervention

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Abstract— Ultrasound imaging is used extensively in diagnosis and image-guidance for interventions of human diseases. However, conventional 2D ultrasound suffers from limitations since it can only provide 2D images of 3-dimensional structures in the body. Thus, measurement of organ size is variable, and guidance of interventions is limited, as the physician is required to mentally reconstruct the 3-dimensional anatomy using 2D views. Over the past 20 years, a number of 3-dimensional ultrasound imaging approaches have been developed. We have developed an approach that is based on a mechanical mechanism to move any conventional ultrasound transducer while 2D images are collected rapidly and reconstructed into a 3D image. In this presentation, 3D ultrasound imaging approaches will be described for use in image-guided interventions.

I. INTRODUCTION

Image-guidance during interventional and surgical procedures has become an important tool in the armament of surgeons and interventional radiologists. Various imaging modalities by themselves or in combination are being used through image registration. Although 2D ultrasound (2D US) imaging has been used extensively for percutaneous interventional procedures and during surgery, it suffers from limitations limiting its use. Nonetheless, the majority of US-based interventional procedures are still performed using conventional 2D imaging.

Over the past two decades, 3D ultrasound (3D US) imaging techniques have been developed based on 1D and 2D arrays. These developments have stimulated the use of 3D US techniques for minimally invasive image-guided interventions and surgery [1]. Advances in 3D US imaging technology have resulted in high quality 3D images of complex anatomical structures and pathology, which are used to improve the guidance of interventional and surgical procedures [2-9]. In this paper we focus on some recent development of 3D US imaging as it applies to image-guided interventions.

II. BENEFITS OF 3D ULTRASOUND IMAGING

In conventional 2D US imaging systems the user can manipulate the hand-held US transducer freely over the body to generate images of the surgical target. This capability is sufficient for many interventional procedures, such as breast biopsy; however, some interventional procedures require 3D image visualization, for the following reasons [10]:

- Manipulating the conventional US transducer freely over the anatomy during the interventional procedure requires that users mentally integrate many 2D images to form an impression of the target imbedded in the 3D anatomy. However, interventions in involving complex anatomy or pathology, may lead to longer procedures and result in variability and inaccuracy in guidance of the interventional applicator to the target.
- Relocating the 2D US image at the exact location and orientation in the body at various times during the procedure is difficult and subject to variability. Since monitoring the progression of the intervention often requires imaging of the same location (plane) of the anatomy, manual manipulation of a 2D US image is suboptimal.
- Conventional 2D US imaging systems do not permit viewing of planes parallel to the skin. Since interventional procedures may require an arbitrary selection of the image plane for optimal guiding the interventional procedure, 2D imaging is suboptimal.

The following sections review two 3D US guided interventional procedures making use of mechatronic systems with advanced image processing tools.

III. 3D ULTRASOUND-GUIDED FOCAL LIVER ABLATION

Increasing hepatocellular carcinoma (HCC) cases have been reported from several Western countries, and the liver is the second most common site of metastatic cancer arising in other organs [11]. Furthermore, HCC is the fifth most common diagnosed malignancy and the third most frequent cause of cancer related deaths worldwide. Incidence is particularly high in Asia and sub-Saharan Africa due to the large incidence of hepatitis B and C, both of which are complicated by hepatic cirrhosis, which is the greatest risk factor for HCC [12].

Surgical resection or liver transplant is the accepted standard therapeutic approach, and currently has the highest success rate of all treatment methods for primary and metastatic liver cancer. Unfortunately, only 15% of patients are candidates for surgery [13, 14]. The use of minimally invasive percutaneous techniques, such as radio-frequency (RF) and microwave (MW) ablation of cancerous lesions in the liver, is a rapidly expanding for patients who are not candidates for surgical resection or transplant.

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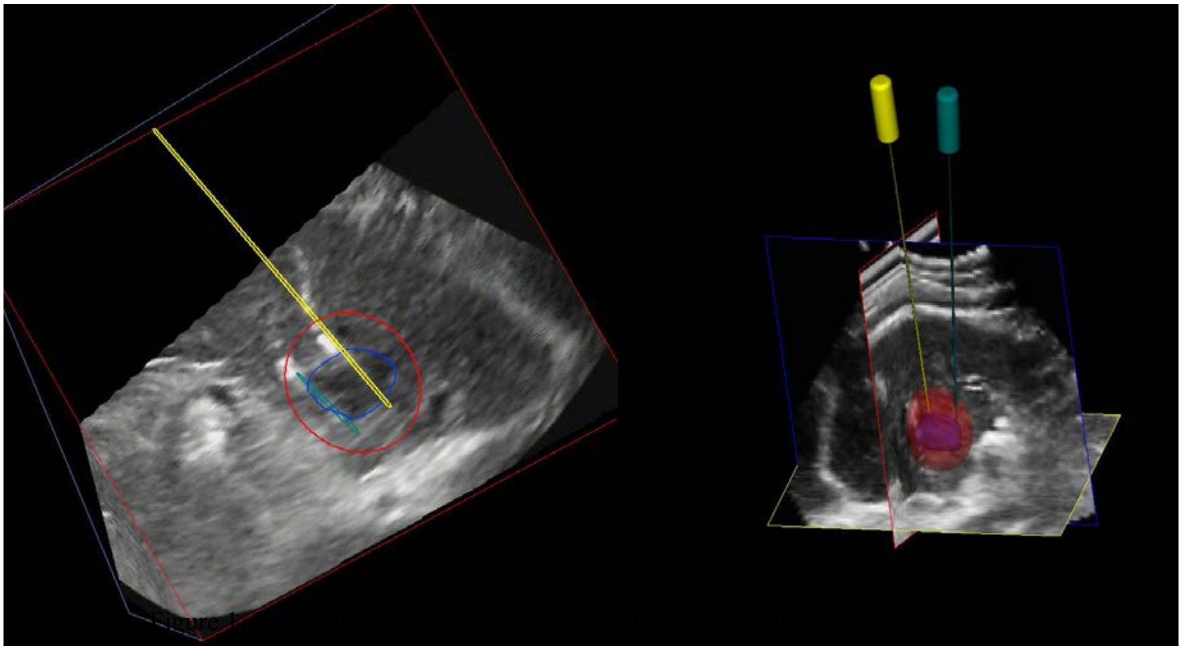

Figure 1. 3D ultrasound image of a primary HCC tumor with microwave applicators in place.

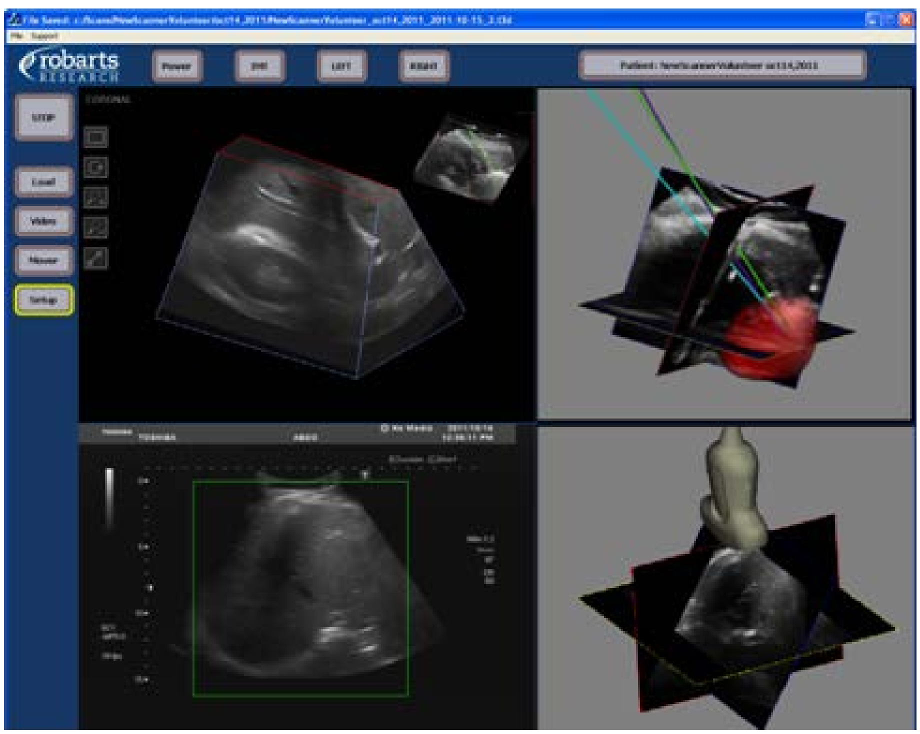

Figure 2. The user interface for the 3D ultrasound guided focal liver ablation system. The top left is the 3D ultrasound image; the bottom left is the live 2D ultrasound image; the top right is the 3D ultrasound view showing the segmented tumor; and the bottom right is the view with the graphical representation of the transducer giving the user the orientation of the transducer relative to the 3D image.

However, these methods have a higher local recurrence rate than surgical resection, primarily due to insufficient or inaccurate local ablation of the tumor.

Accurate placement of the RF or MW applicator is critical for complete ablation of the tumor [15]. In the USA, the standard-of-care makes use of CT imaging for planning and guidance. However, this approach requires the use of a CT scanner for a few hours, which is not always possible in developed countries and particularly in developing countries, where access to CT is limited.

We have developed a 3D US guidance system for focal treatment of liver tumors. The use of 3D US-guidance for focal liver tumor ablation makes use of the ability of 3D US show the features of liver masses and the hepatic vasculature, allowing accurate guidance of the ablation applicators to the target [16]. 3D US also allows accurate monitoring of the ablation zone during the procedure and at follow up.

The 3D US system we developed consists of an electro-mechanical motor -encoder assembly to move a conventional 2D US transducer by tilting, linear translation, or hybrid motion combining tilting with translation. Images from the US machine are acquired into a PC via a digital frame grabber and reconstructed into a 3D US image as the 2D US images are acquired.

Software tools are used to provide registration of the pre-operative CT to intra-operative 3D US images, and tracking of the ablation applicators during insertion into the liver towards the target (see Figs. 1 and 2). Previously acquired contrast enhanced CT images can be registered with intra-procedural 3D US images allowing targeting liver tumors not visible in US, but visible in CT images.

4. 3D Ultrasound-guided prostate biopsy

Worldwide, prostate cancer (PCa) is the second leading cause of death due to cancer in men, accounting for between 2.1% and 15.2% of all cancer deaths [17, 18]. When diagnosed at an early stage, the disease is curable, and even at later stages treatment can be effective. Thus, early diagnosis, accurate staging of prostate cancer, and appropriate therapies are critical to the patient's well-being.

Prostate biopsy using transrectal US (TRUS) is the definitive method for diagnosing PCa. Since, many small tumors are not detected by TRUS, biopsy samples are obtained from predetermined regions of the prostate. Although used extensively, this approach is suboptimal as reports have shown that the false negative rate ranges as high as 25%.

We have developed a mechanical 3D US-guided biopsy system that makes use of MR images obtained before the biopsy procedure and registered to the intra-procedural 3D US image to allow targeting of MR identified tumors, but guided by US imaging [19]. Our mechanical guidance system is based on an articulated multi-jointed stabilizer and a transducer tracking mechanism that has 4 degrees-of-freedom (DOF) and has an adaptable cradle to support any commercially available end-firing TRUS transducers used for prostate biopsy. The system allows real-time tracking and recording of the 3D position and orientation of the biopsy needle as the physician manipulates the TRUS transducer (see Figs. 3 and 4).

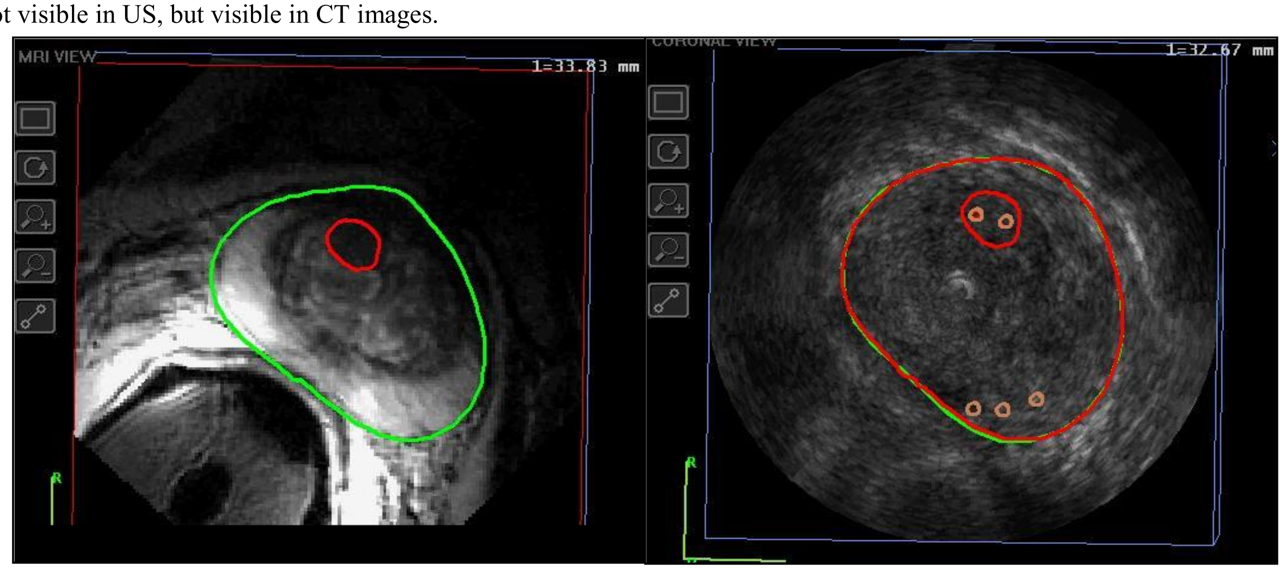

Figure 3. 3D ultrasound image of the prostate. (left) Segmented MR image of the prostate with the tumor outlined. This image was registered to the 3D ultrasound image shown in the right panel. (right) Segmented 3D ultrasound image of the prostate with the segmented tumor transferred to it from the MR image. The small circles show where the radiologist performed the biopsy.

To perform a 3D US-guided prostate biopsy, a conventional end-firing US transducer is mounted onto the tracking assembly. The physician inserts the TRUS transducer into the patient's rectum and rotates the transducer 180 degrees about its longitudinal axis to generate a 3D US image. The 3D US image is then registered to the pre-procedural acquired MR image with the outlined tumor to be targeted. After the biopsy targets are selected, the trajectory of the biopsy needle is guided by the system and fired to obtain a core. The location of the biopsy is then recorded.

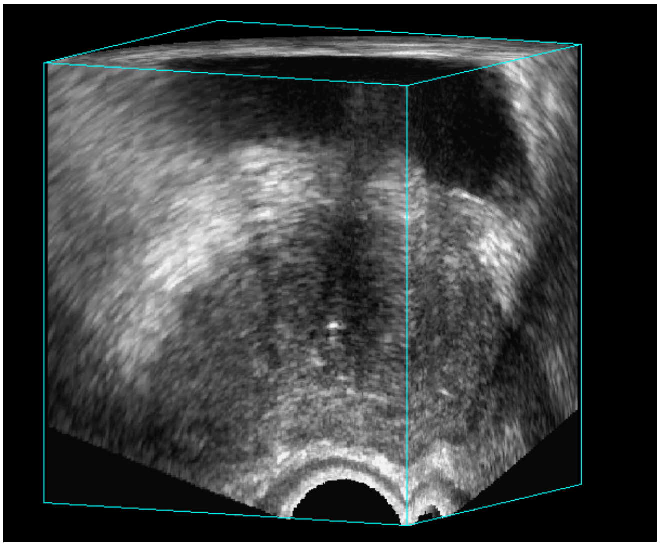

Figure 4. 3D ultrasound image obtained with a mechanical mechanism that rotated the TRUS transducer around its long axis over 180 degrees. The 3D image is reconstructed as the 2D ultrasound images from the ultrasound machine are acquired. The 3D scanning takes about 8 seconds

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