# Enabling 3D Ultrasound Procedure Guidance through Enhanced Visualization*

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**Abstract.** Real-time 3D ultrasound (3DUS) imaging offers improved spatial orientation information relative to 2D ultrasound. However, in order to improve its efficacy in guiding minimally invasive intra-cardiac procedures where real-time visual feedback of an instrument tip location is crucial, 3DUS volume visualization alone is inadequate. This paper presents a set of enhanced visualization functionalities that are able to track the tip of an instrument in slice views at real-time. User study with *in vitro* porcine heart indicates a speedup of over 30% in task completion time.

**Keywords:** 3D ultrasound, electromagnetic tracking, graphic processing unit, instrument navigation, mosaicing, slice view.

## 1 Introduction

Real-time 3D ultrasound (3DUS) offers important advantages for guiding diverse medical procedures. Foremost is the ability to visualize complex 3D structures [1]. Studies have shown that real-time 3DUS is more efficient and accurate than 2DUS for basic surgical tasks and can enable more complex procedures [2]. Imaging rates up to 30 volumes per second also enable good visualization of instrument-tissue interactions, far faster than the volumetric imaging alternatives (MR and CT scans). Fluoroscopy provides fast frame rates, but only has a limited number of 2D views, requiring the clinician to mentally combine them to derive 3D structure. Unlike fluoroscopy, 3DUS also allows visualization of the soft tissues, and avoids the use of ionizing radiation. 3DUS is easily integrated into procedures as the small probe can be readily placed at the point of interest. Finally, costs are also far lower, with top-of-the-line 3D ultrasound machines costing far less than comparable fluoroscopy, CT, or MR systems.

Despite these evident advantages, a decade after its commercial introduction, 3DUS is rarely used clinically for procedure guidance. There has been a broad

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spectrum of research in 3DUS guidance, in diverse areas including liver surgery [3] [4], liver ablation [5], kidney imaging [6] and cardiac imaging [7][8][9]. Nonetheless, 2D ultrasound is still the prevailing choice in hospitals [1]. The reasons for this surprising lack of acceptance of 3DUS are diverse. One clear drawback of 3DUS is limited resolution. While voxel sizes are less than one millimeter, noise and distortion typically make it hard to discern features smaller than a few millimeters. In addition, 3DUS images are typically displayed as volume-rendered images. While this is effective for visualizing tissue surfaces surrounded by fluids as in obstetrics and cardiology, volume rendering can accentuate the distortion and noise inherent in 3DUS imaging [10], resulting in irregular surfaces and difficulty in distinguishing instrument artifacts [11][12]. Volume rendering is also problematic for visualizing the internal features of solid organs like liver and kidney, where the entire organ produces textured reflections that fill the imaging volume. Another limitation is the small field of view. Because of the inherent tradeoff in ultrasound imaging between volume size, resolution and frame rate, the volume size is inherently limited.

We hypothesize that enhanced displays can overcome key limitations in current 3DUS guidance, and bring the benefits of 3DUS to a broad range of procedures. One way to address the lack of surface definition and the difficulty in distinguishing instrument from tissue in volume rendered images is to display a cut plane image or "slice" from the 3DUS volume that contains the instrument tip. Because this cross-sectional view shows the point of contact of the instrument with the tissue, as well as adjacent tissue regions, the clinician can determine the specifics of the tool-tissue interaction. Manually selecting planes within the 3DUS volume that contain the instrument tip, however, is highly challenging, particularly as the instrument moves within the volume. The ability to automatically visualize these slice views would greatly enhance the usability of 3DUS.

In addition, research efforts on mosaicing multiple 3DUS volumes to create an extended field of view have been recently reported [13][14]. We further hypothesize that integrating slice views with a mosaiced volume would enable 3DUS for more complex interventions, particularly those requiring navigation across regions larger than a single 3DUS volume.

In this paper, we describe the design of a system for tracking the catheter tip to enable continuous display of exactly the right slices. We report the results of a user study that indicates the potential of such enhanced displays in improving the efficacy of real-time 3DUS guided procedures. In the next section, we present the system design, followed by user study and results. We conclude the paper with a discussion of implications for the design of procedure guidance systems.

## 2 System Design

### 2.1 System Configuration

To demonstrate the potential benefits of slice views and mosaicing for procedure guidance, we implemented a prototype visualization system. We used Philips 3DUS scanner iE33 with the X7-2 2D/3D probe, imaging at 8.1cm and 35Hz with a volume size of 112x48x112 voxels (Philips Medical Systems, Andover, MA). An electromagnetic (EM) tracking system (3D Guidance trakStar System, Ascension Technology Corporation, Burlington, VT) tracked the trajectories of the 3DUS probe and the instrument tip. Image processing and rendering (Fig. 1) was done on a GPU

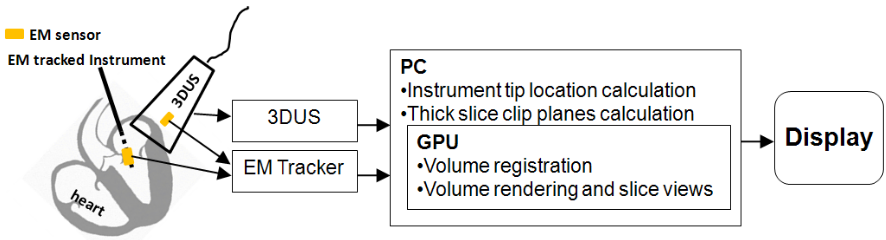


**Fig. 1.** System Overview

enabled computer (Dell Alienware Aurora, Intel Core i7 processor at 2.67GHz, 6GB RAM, NVIDIA GTX260 graphics card).

### 2.2 Calculation of the Instrument Tip Inside the 3DUS Volume

The system performs real-time 3DUS volume mosaicing to generate an extended field of view [14]. The instrument tip location can be registered to the mosaiced volume or an input volume. An EM sensor is attached rigidly at the tip of the instrument, with the EM sensor *x*-axis aligned with the shaft of the instrument. Another EM sensor is attached rigidly to the 3DUS probe. $T_{US}^{EM}$ is the transformation matrix between the 3DUS probe and EM sensor. It is derived through a calibration procedure where we scan a triangle wire frame phantom with known geometric dimensions and perform intensity based registration.

There are three coordinate frames involved in the system: US, EM sensor, and EM transmitter (Fig. 2). Assume $P^{US}$ is the voxel in the ultrasound volume that corresponds to the tip of instrument, $P^{Transmitter}$ is the EM sensor reading from the tip of instrument, and $S$ is the scaling matrix that converts the ultrasound volume from voxel unit to a physical unit. The overall transformation can be established as the multiplication of series homogenous transformation matrices

$$T_{EM}^{Transmitter}\ T_{US}^{EM}\ SP^{US} = P^{Transmitter} \tag{1}$$

The tip location in the ultrasound volume can then be derived as

$$P^{US} = S^{-1}{T_{US}^{EM}}^{-1}{T_{EM}^{Transmitter}}^{-1}P^{Transmitter} \tag{2}$$

EM tracker provides six degree of freedom readings of the sensor location. The orientations of EM sensor's three orthogonal axes ($X_{EM2}, Y_{EM2,} Z_{EM2}$) (Fig. 2) are used to generate the initial orthogonal slice views that contain the instrument tip. Users then have the option to further adjust the orientation and thickness of each of the slice.

### 2.3 Slice Views

The system tracks the instrument tip position and three orthogonal orientations at real-time. The tip can be displayed in an input volume or within a mosaiced volume using the real-time mosacing techniques we developed [14]. Fig. 3a shows the four input volumes from different point of views that contributed to the mosaiced volume shown in Fig. 3b, where the entire left atrium of a porcine heart can been seen. The tip of instrument is inside the atrium, but blends in with the surrounding tissues. In Fig. 3c, the tip of the instrument is highlighted in green. Cut planes for the slice views can also be visualized as in Fig. 4. Once the desired cut planes are identified, the user can switch to the slice views that shows the tissues highlighted in a different color transfer function as shown in Fig. 5.

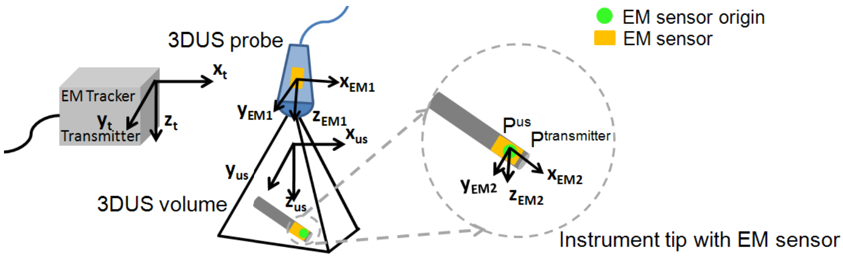


**Fig. 2.** Coordinate transformations for instrument tip location

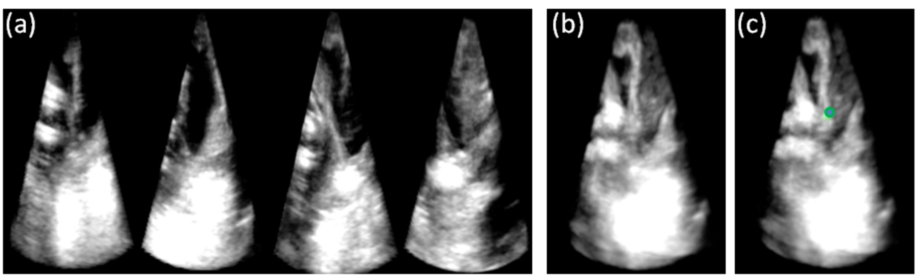


**Fig. 3.** 3DUS volumes of left atrium. (a) Input volumes. (b) Mosaiced volume with instrument. (c) Mosaiced volume with instrument tip highlighted as a green dot.

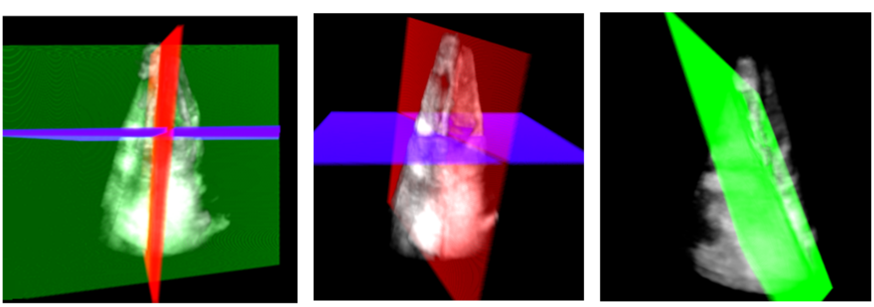

**Fig. 4.** Orthogonal slice view cut planes through the instrument

# 3 User Study

We conducted a user study, following a protocol approved by our institutional review board, comparing performance in clinical tasks with and without the enhanced displays. To provide a specific clinical focus, the tasks are taken from intra-cardiac procedures as this specialty shows strong potential for benefiting from 3DUS guidance, however, as discussed below, the proposed display system can apply to a range of other procedures.

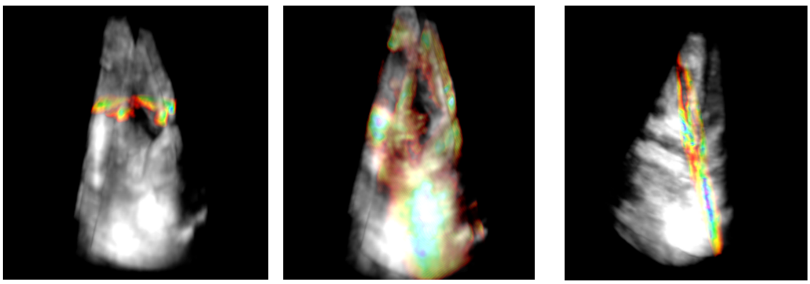

**Fig. 5.** Orthogonal slice views (in non-gray color map) showing the instrument and its surrounding tissue. The colors correspond to the intensity values.

## 3.1 Study Design

Five interventional cardiologists with experience in minimally invasive cardiac procedures were recruited for the user study. Their experience in conducting procedures ranged from 3.5 years to 11 years after the beginning of postgraduate training. Each subject performed two instrument navigation tasks in a water tank. Subjects could not directly see the task by eye. There were three 3DUS display conditions: the volume rendered display on the 3DUS machine alone, volume rendered with slice views, and slice views in the mosaiced volume. The order of the tasks and displays for each subject was randomized. In the first two display conditions, subjects moved the probe with one hand to follow the moving instrument and keep it in the 3DUS field of view. With the mosaiced display, there were two options. If the imaging object was static, the user could simply use the EM tracker generated slice views in the mosaic. With moving imaging object, such as a beating heart, the real-time 3DUS volume would be superimposed on the mosaic. In this study, since the image objects were static, subjects did not hold the US probe during the third testing conditions.

Catheter based ablation procedures such as atrial fibrillation (AFib) ablations aim to create linear destructive lesions in the tissue around the pulmonary veins to prevent propagation of an abnormal electrical signal to the rest of the atrial tissue [15]. The first task was to trace the perimeter of the rectangle created by four rubber bands (Fig. 6a) with the tip of a catheter in a water tank. The dimensions of the rectangle were roughly 40mm x 30mm. The goal of this task was to evaluate the effectiveness of the slice views in improving user's ability to maneuver the catheter tip along a predefined path. Rubber bands were chosen because their 3DUS images (Fig. 6b) show significant noise and blurring along the edges, representative of *in vivo* conditions where noise and artifacts are common. The subjects were instructed to hold the catheter roughly 5 cm above its tip, and move the tip along the loop ABCD as outlined in the blue dotted lines in Fig. 6a.

The second task was to trace the mitral annulus of a porcine heart in a water tank using a rigid instrument. An instrument with straight and rigid tip was inserted through a puncture created on the left atrial appendage to access the mitral valve annulus (Fig. 7). In minimally invasive beating heart mitral valve repairs such as mitral annuloplasty, an anchor driver can be inserted through the left atrial appendage to reach the mitral annulus under 3DUS guidance [16]. Although the procedure is promising, instrument tip and tissue often blend together along the atrial wall. This makes it difficult to discern the instrument tip. This task aims to assess the value of slice views and mosaicing for such procedures.

Task completion time was recorded for each subject trial. The instrument tip trajectories were also recorded with EM tracker.

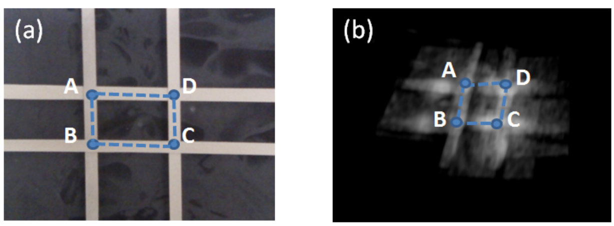


**Fig. 6.** Navigation task 1. (a) Photograph of the rectangle (40mm x 30 mm) created by four rubber bands. (b) Mosaiced 3DUS image of the four rubber bands containing the rectangle.

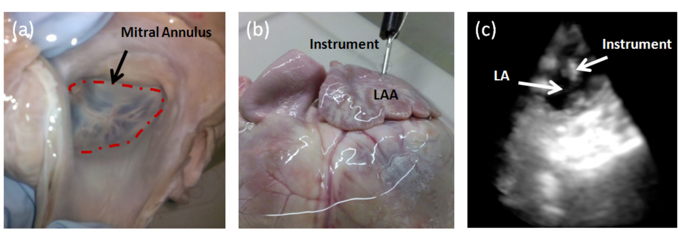


**Fig. 7.** Navigation task 2. (a) Top down view of the mitral valve and mitral annulus. (b) Instrument inserted through the left atrial appendage (LAA). (c) 3DUS volume rendered showing the left atrium (LA) and part of the instrument.

## 3.2 Results

Typical trajectories for both tasks are shown in Fig. 8. The completion times from all subject trials were analyzed using Wilcoxon rank sum test (Fig. 9). The criteria for statistical significance was $p \leq 0.05$. The mean deviation of the trajectory ($D_{mean}$) for task 1 was also calculated by first measuring each line segment AB, BC, CD and

DA (Fig. 6a), and then calculating the mean of the distance from each point on a given trajectory to the corresponding line segment.

In task 1, compared to the completion time under 3DUS volume without slice views, the completion time decreased by 46% with slice views ($p \leq 0.0159$), and $D_{mean}$ decreased by 20%. The completion time decreased by 69% using mosaiced volume with slice views ($p \leq 0.0079$), and $D_{mean}$ decreased by 25%.

In task 2, compared to the completion time under 3DUS volume without slice views, the completion time decreased by 36% with slice views ($p \leq 0.0317$). The completion time decreased by 46% using mosaiced volume with slice views ($p \leq 0.0159$). In both tasks, the variability of the results (standard error) also decreased with enhanced displays. This suggests that with slice and mosaic displays, the surgical task is less dependent on each user's individual echocardiography skills and experience.

Subjects reported that the three orthogonal views were intuitive. All subjects stated that mosaiced volumes combined with slice views have great potential for 3DUS guided interventions.

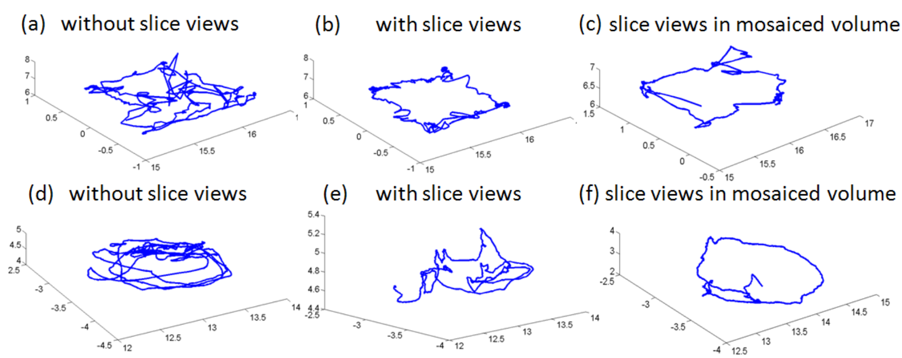


**Fig. 8.** Typical instrument tip trajectory. (a) - (c) Trajectory of tracing the rectangle rubber bands. (d) - (f) Trajectory of tracing the mitral annulus.

# 4 Discussion

In this paper, we aim to address the following three key issues in current 3DUS guidance: (1) Volume rendering alone is not adequate to visualize tool-tissue interaction; (2) Slice view avoids problem with volume rendering, but is difficult to align manually; (3) 3DUS has a small field of view and is difficult to navigate. Our prototype system and user study demonstrate that improved visualization techniques could mitigate key limitations in 3DUS. A mosaiced volume overcomes 3DUS limited field of view and can be used for broad navigation. Computer assisted instrument tip tracking in slice views facilitates real-time instrument navigation and visual feedback.

The slice view features developed are still in the research stage. Further development is needed to ultimately improve the end user's experience. The tasks used here are simpler than clinical catheter based procedures and 3DUS imaging in a water tank has better quality than *in vivo* situations. Thus, we expect even better user improvement with slice views and mosaicing in *in vivo* and clinical procedures.

A number of image-guidance systems share features with the approach presented here. For example, 3DSlicer [17], was originally applied to neurosurgery, where tracked instrument positions are superimposed on static preoperative brain images. These systems necessarily used slice views. Similarly, ultrasound visualization tools such as Stradwin and Stradx [18] work with prerecorded data. The system proposed here, however, uses real time volumetric data, which presents significant challenges for real-time registration, mosaicing, and tracking.

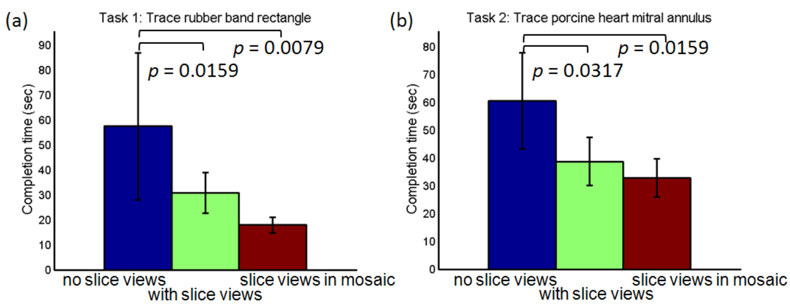


**Fig. 9.** Task completion times. (a) Task 1 – trace rubber band rectangle. (b) Task 2 – Trace porcine heart mitral annulus.

### 4.1 System Extensions

Novotny *et al.* developed a GPU based real-time instrument detection algorithm that uses a generalized Radon transform [19]. Any such image-based tracking approach can be advantageously integrated with the current EM tracker based slice views. The EM sensor provides the initial estimate of the tip location, which reduces the image search space hence further speed up the algorithm.

Accuracy of the volume mosaicing could also be further improved using image based methods. Schneider *et al.* developed a real-time feature-based 3DUS registration framework on GPU [20]. Grau *et al.* reported a structure orientation and phase based algorithm to register apical and parasternal 3DUS datasets of the heart [21]. EM based volume registration can be used as an initial estimate for either of these two algorithms.

### 4.2 Application to Beating Heart Procedures

The slice views presented here can be integrated with an ECG gated mosaicing system for beating heart intra-cardiac procedures [14]. ECG gating captures the heart motion in a complete cardiac cycle.

Currently in a typical catheter based AFib ablation procedure, a 3D electrophysiological model resembling the shape of the atria is generated by recording the locations of the ablation catheter's tip in space. The point clouds are then registered to a CT or MRI based pre-operative anatomic model (e.g. CARTO, Biosense Webster, Diamond Bar, CA). However, this mapping and model creation can be a tedious process and fluoroscopy is routinely used. An ECG gated 3DUS mosaicing system combined with enhanced user display such as slice views could shorten the procedure time, reduce human exposure to fluoroscopy, and provide improved visualization on tool-tissue interaction.

## 5 Conclusion

In this paper, we presented a set of enhanced display modalities for real-time 3DUS visualization. The system integrates EM tracking systems and GPU implementation for real-time instrument tip cut plane tracking to mitigate the 3DUS distortions inherent in conventional volume rendering. Our user study and participants’ feedback demonstrate the potential of such enhanced visualization in instrument navigation and procedure execution with 3DUS guidance.

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