Real-time Visualized Vessel and Catheter Path Reconstruction for Intravascular Intervention

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Abstract— **Minimally invasive intravascular intervention is performed with the aid of catheters for therapy. We apply intra-operative freehand ultrasound and tracked catheter for guiding intravascular intervention. Current freehand 3D ultrasound techniques separate the scanning or acquisition step from the visualization step. This leads to no feedback during image acquisition. The reconstruction quality is highly dependent on scanning experience. A low-quality imaging even causes re-scanning and prolongs the time of image acquisition. In addition, the catheter path is important information implying the skeleton of the target vessel. It also helps doctor understand the catheter position relative to vessels for reducing the risk of vessel injuries. We developed a catheter navigation system that will allow real-time visualizing the scanned vessel volume as well as catheter path. The system consists of a freehand US for vessel reconstruction, an electromagnetic tracking system for locating the position and orientation of the ultrasound probe and catheter tip, a video frame grabber for capturing ultrasound frames, and a typical PC for performing real-time reconstruction and scene rendering. The system incorporates novel methods for visualizing data acquisition of image guided intravascular intervention in real time. This paper reports on current work in progress, and focuses on methods to achieving real-time visualizing reconstructions of freehand 3D ultrasound and catheter path. We demonstrate the system on a vessel phantom. The results suggest the system could visualize the reconstruction in real-time.**

Keywords— **Real-time, Freehand ultrasound, Visualization, catheter path.**

I. INTRODUCTION

Minimally invasive intravascular intervention is performed with the aid of catheters for therapy. One of the main challenges is the location of these catheters during the procedure. The most commonly used technique is, contrast agent and 2D angiography. The major drawbacks of the technique come from its high costs, no depth information and the use of potentially harmful radiation. To overcome these limitations, Ultrasound (US) has been introduced as an alternative localization method. The major advantages of the technique come from short image acquisition time, safety and relatively low acquisition and maintenance costs. A step-up of conventional 2D US is the emerging 3D US technology. The volumetric data from 3D ultrasound can be extremely helpful for navigation task.

We originally proposed a catheter navigation system combining 3D US and electromagnetic (EM) tracking system. A freehand US imaging system provide a vessel volume by reconstructing tracked US Doppler images. An EM tracking system detects the positions and orientations of the catheter tip. Catheter path is important information for the doctor. On the one hand, US images commonly suffer from artifacts. Catheter path provides a proof confirming the position and orientation of the reconstructed vessels because the catheter is typically placed in vessels. On the other hand, the risk of vessel injuries caused by the catheter depends very much on its position. So knowing the catheter path makes the catheter placement more apparent.

In order to acquire a vessel volume and catheter path, the target vessel is reconstructed by freehand scanning, and the path is reconstructed by EM tracking system. This method leads to the following problems: (a) the conventional freehand technique separates the acquisition, reconstruction and visualization steps [1]. The reconstructed volume is unknown until the scanning, reconstruction and visualization are completed. Consequently the acquisition quality is highly dependent on scanning experience, which may result in low-quality imaging even re-scanning. To acquire high image quality, the re-scanning prolongs the time of data collection, which causes a tedious procedure. Although some groups reported their solutions [2, 3], the architecture of GPU complicated the programming. In addition, the predefined dimensions of the scanned volume limited its application in complex clinical requirements. (b) During acquiring catheter path, a vessel model is needed to help users understand the relative relationship between the catheter tip and the target vessel. The catheter path has to be acquired after vessel reconstruction. This leads to a complicated procedure in data acquisition and extends the intra-operative time.

Our primary focus in this work is to demonstrate how real-time visualized 3D ultrasound reconstruction can be performed on standard computer hardware, and furthermore how the reconstruction can be integrated into a 3D scene to

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guide catheter path acquisition while data collection is taking place.

II. MATERIALS AND METHODS

A. Materials

The materials in our experimental design are shown in Fig. 1: An EM tracking system (NDI, Aurora, Canada), a US scanner (Prosound α 10, Aloka, Japan), a catheter (1.3mm diameter) and a PC with an Intel core i7 2.93GHz CPU for collecting US images and EM tracking data. The EM tracking system included two 6 degree of freedom (6DOF) sensors. One was embedded in the catheter tip for detecting its positions and orientation, and the other was mounted on a 2D convex US probe for constructing the freehand US system. An image grabber (PCI5531, Interface, Japan) was equipped on the PC for capturing US images. The data acquiring module was developed with MFC and the rendering module was developed based on the surface rendering framework of VTK [4].

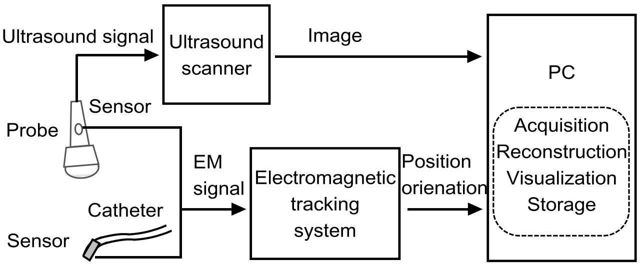

Fig. 1 System configuration

B. Work flow

This system interactivity was implemented by decomposing the application into several threads that run in parallel, and by ensuring proper synchronization of data transfers between the threads. The navigation system had four threads to process image and data (Fig. 2).

- Thd1

  This thread communicated with image grabber for acquired US images. A memory buffer was allocated to save the newly acquired images. The thread also displayed the image to screen for monitoring the work condition of the image grabber.

- Thd2

  This thread communicated with AURORA tracking system for acquiring tracking information of the freehand probe and the catheter via the serial port. The tracking information of the two tracked objects was both converted to vectors containing three parameters for translation and four for rotation. The vectors were shown on the user interface to confirm the communication condition of the tracking system. Each vector was placed onto a pre-allocated stack along.

- Thd3

  Once new US image and tracking data were acquired, this thread saved them at the hard disk as AVI and TXT files respectively. Each frame of the tracking data was attached with a time stamp for synchronization.

- Thd4

  During the US images and tracking data were saved, the rendering thread reconstructed the image points and path points in the world coordinate frame in a loop process. This process included the image segmentation, tracking data analysis, image and path point interpolation and the final scene rendering. Spinlocks (a “mutex lock” in modern programming terms) were used to ensure that both the saving thread and the rendering thread could safely access the image and tracking data.

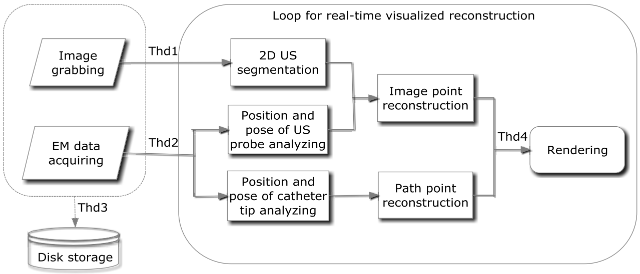

Fig. 2 Processing flow

C. Image and data acquisition

The US video was grabbed into the navigation system with 640×480 pixels at 30 fps. The EM tracking system transferred the position and pose of two tracked sensors to the navigation system at 23 fps. During the probe scanning, the position and pose of the US probe and 2D image are synchronized with same time stamp.

D. Visualized reconstruction

Before reconstruction, a calibration was performed so as to estimate the transformation between the attached EM sensor and the 2D US probe. The US scanner worked at Power Doppler (PD) mode. When scanning the vessel, the

Doppler signal and the B-mode signals are combined on the display of the US scanner. The US images were segmented by extracting all colored pixels in the imaging region. After converted RGB to identical grayscales, these extracted points in 2D images were mapped into physical space by using the following equation.

$$X_{phy} = T_{phy}^{sen} \cdot T_{sen}^{img} \cdot S \cdot X_{img} \quad (1)$$

The point in US image X_{img} is first scaled by S. It is mapped in sensor space by the rigid transformation T_{sen}^{img}, then into physical space by T_{phy}^{sen}. That is X_{phy}, the position based on the EM coordinate system (the world coordinate system). These mapped image points were interpolated into the physical space with spacing of 0.5×0.5×0.5mm and saved as spatial points with PNN [5]. An array was built for saving these spatial points. If a newly acquired spatial point had a physical position which had existed in the array, this point would be discarded.

The catheter path was reconstructed by collecting the position of the sensor embedded in the catheter tip. A path point array was built for saving these physical positions. If the newly acquired path point had a distance over 1mm from the last saved path point, the acquired path point would be saved in the array, otherwise, discarded.

E. Image and data storage

During acquiring and visualizing the image and tracking data, the tracked US images and tracking data of sensors were recorded simultaneously. The US images could be used for a high quality reconstruction. The catheter path could be analyzed offline.

III. EXPERIMENTS AND RESULTS

A vessel phantom evaluation was performed. A 3D model of a vessel was designed with 3D CAD software (Inventor, Autodesk, Inc. USA) (Fig. 3 A). Then the designed model was made up with a resin (FullCure930, Objet, Israel) by 3D printer (Eden260V, Objet, Israel). The made vessel phantom was surrounded by a coupling media mixing distilled water, agar and black lead. Fig. 3 B shows the final vessel phantom. A blood mimicking fluid (BMF–US, Shelley, Canada) was cycled to produce a blood stream by a pump (Masterflex L/S, Cole-Parmer, USA) at a flow rate of 900ml/min. The US probe scanned the vessel phantom at PD imaging mode. During the scanning, the US images and tracking data of the US probe were recorded simultaneously. At the same time, the scanned vessel sections were visualized in real time (Fig. 4 A). After scanning, the pump was stopped, and the catheterization was performed. During the positions and orientations of the catheter tip was be saving, the catheter path was superimposed on the visualized vessel image (Fig. 4 B). Fig. 5 shows a result of reconstructing the vessel from the saved US images.

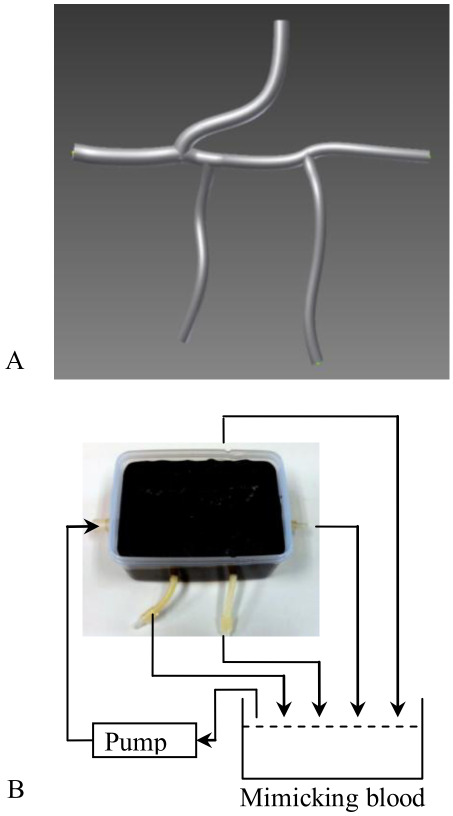

Fig. 3 A: vessel model was designed with three bifurcations. B: experiment configuration.

We calculated the frame rate of saving and visualizing process. A 2GB AVI saving took around 78s. The associated tracking records were around 1800 frames. The saving frame rate reached 23 fps. During saving images and tracking data, the visualizing frame rate reached 15~23 fps.

IV. DISCUSSIONS

The visualized reconstructions of freehand US and catheter path facilitate the image and tracking data acquisition. The visualizing process reaches a real time rendering without interrupting the acquisition and storage processes.

The method also allows us to acquire the feedback of data collection. The intensity of interpolated image points and the gaps between cross sections suggests the quality of reconstructed US volume. Consequently we can scan vessels interactively to obtain a high quality volume. In addition, our method interpolates image points into physical space directly, not into a predefined volume. Compared with previous studied, there is no constraint that the scanning is limited in a fixed space. The different parts of target vessel can be scanned respectively for achieve a high quality reconstruction. The overlaid catheter path implies the skeletons of the target vessel. The registered image points from vessel and the catheter path help the users acquire data in a complex vessel network interactively.

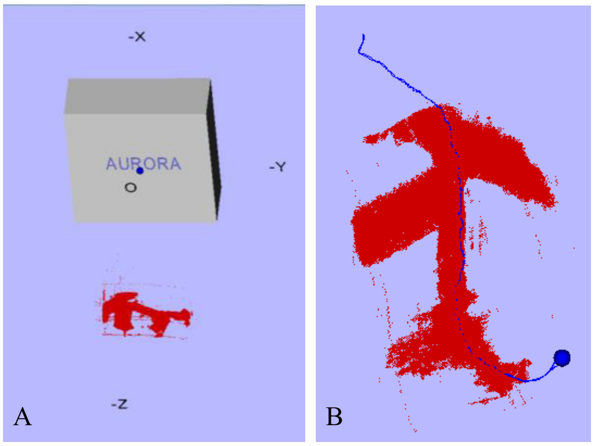

Fig. 4 Results of visualized reconstruction. A: The image points on Doppler image were interpolated into physical space and rendered with red points. B: The positions of the catheter tip was reconstructed and rendered with blue lines.

Fig. 5 Result of reconstruction from saved US images.

V. CONCLUSIONS

We have presented the implementation of a real-time visualization for vessel volume and catheter path reconstructions and evaluated the method with a vessel phantom. The method uses the point visualization to implement the visualized data acquisition, which facilitates the freehand reconstruction and catheter path acquisition. The evaluations demonstrate the reconstruction and rendering speed can reach 15~23 fps without interrupting data acquisition and storage. Using the method, we can not only get real-time visualized feedback on the acquisition and reconstruction during scanning, but also complete the 3D imaging within the data acquisition time for catheter path reconstruction. In the future, we will improve the visualizing quality and integrate the image fusion between the pre- and intra-operative images.

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