Electromagnetic Navigation for Thoracic Aortic Stent-graft Deployment Using Tracked Ultrasound

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Abstract— **This research proposes an electromagnetic navigation system for thoracic aortic stent-graft deployment. The system employed patient's preoperative image (CT) to construct a 3D cardiac model based on a GPU acceleration technique. Then a preoperative planning is performed on the cardiac model. During the surgery, we employ electromagnetic tracker to trace the sensors which are embedded in the catheter and ultrasound probe, when a landmark based registration is used to map the patient's coordinate to image coordinate in real-time. In order to "see" the real condition of inter surgical environment, an intra-operated ultrasound image is fused to the cardiac model by using a calibration panel to compute the transform from 2D ultrasound image coordinate to coordinate of sensor which was attached to the ultrasound probe in a virtual reality environment.**

Keywords— **Electromagnetic navigation, GPU accelerated cardiac modeling, preoperative planning, and ultrasound probe calibration.**

I. Introduction

Thoracic aortic stent-grafts have been approved for use in some developed country for the treatment of aneurysms in the thoracic descending aorta these years. Their worldwide use lead to many dissections and researches during the past years[1-4]. But traditional thoracic aortic stent-graft deployment uses X-ray to guide the surgery. This method has two mainly disadvantages. The first is that both the surgeon and the patient are exposed under the X-ray. Secondly, the X-ray only gives the 2D view which just provides limited information to guide the surgery.

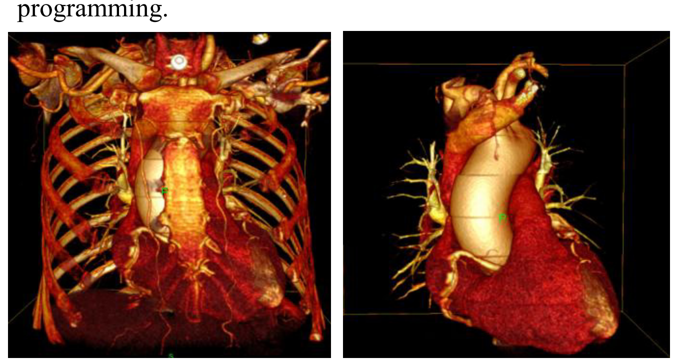
However, electromagnetic navigation systems have been increasingly developed to be used in surgical field [5][6]. These navigation systems can track the surgical instruments in real-time. They can provide precise position and orientation of surgical instruments, endoscopic, and interventional devices inside patient's body. Meanwhile, ultrasound (US) image can provide real-time anatomical structure and situation inside the patient's body. But US only can hardly trace the probes and the target due to its low image quality and limited view field. Therefore some researchers combined the navigation system, which constructed virtual reality(VR) , with intra-US image to guide the surgery. Linte et al [7] developed a navigation system and introduced US image into the system to construct an augmented VR guidance for off-pump, closed, beating intracardiac surgery in phantom. Xishi Huang et al [8] researched the registration between dynamic 2D US and 3D CT image of beating heart in phantom and animal.

The approach proposed in this paper was inspired by these works to combine the electromagnetic navigation with US image for the deployment of stent-graft for treatment of thoracic aortic aneurysms instead of the traditional X-Ray guidance. Patient's preoperative image (CT) was employed to construct a 3D cardiac volume model where the preoperative planning was performed. Under the guidance of the electromagnetic tracking system combined with the real time US image, surgeon can deploy the stent-graft into the target position confidently without X-ray.

II. MATERIALS AND METHOD

A. GPU Accelerated Cardiac Modeling

In order to provide more intuitive information, patient's preoperative images (CT) were employed to construct a 3D cardiac volume model with customized GPU acceleration. The patient's images were rendered by a raycasting algorithm, where implement the GPU acceleration with CUDA(Compute Unified Device Architecture) programming.



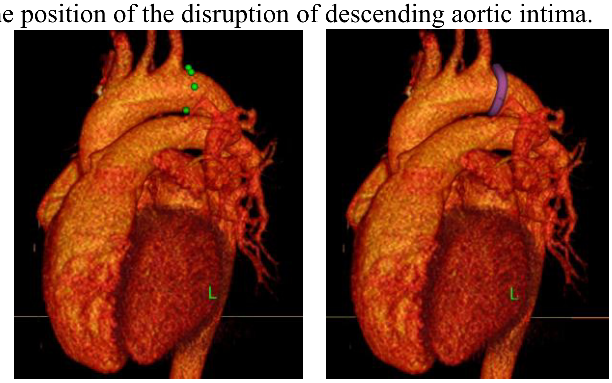
(a) (b)

Fig. 1. GPU accelerated cardiac modeling. (a) The GPU accelerated raycasting volume rendering. (b) A result of GPU accelerated cardiac modeling

The heart and aorta from preoperative CT image are segmented and displayed using the GPU accelerated volume rendering to reconstruct the model shown in the Fig. 1.

B. Preoperative planning

The target position to deploy can be considered as a plane where the top plane of the stent-graft should fit, where the stent-graft is similar to a cylinder when it unfolded. The cross section between the target plane and the aorta is approximately a circle. Therefore the task of preoperative planning is actually to define the plane (circle) which is at the position of the disruption of descending aortic intima.



(a) (b)

Fig. 2. The preoperative planning. (a) Points on the target. (b) The created target plane.

After analysis of patient's preoperative images (CT), surgeons define the target position on the volume model of aorta. Then a set of points are evenly distributed on the circumference (Fig. 2a) of the side of aneurysm which are closest to the arteries on the aorta arch. These points can then be used to define a plane (Fig. 2b) using the least squares method. This plane is the target position where the stent-graft will be deployed.

C. Probe Calibration of US

In order to fuse the intra-operative US image with the preoperative CT image and the cardiac model to assist the navigation, the probe calibration should be done to gain the transformation from the US image coordinate to the tracking device (the sensor attached to the probe and tracked by electromagnetic tracker) coordinate. A point in US image transformed to the world coordinate can be represented by:

$$\begin{pmatrix} x_w \\ y_w \\ z_w \\ 1 \end{pmatrix} = TM_{w\leftarrow td} \bullet TM_{td\leftarrow ui} \begin{pmatrix} s_x \bullet u_k \\ s_y \bullet u_v \\ 0 \\ 1 \end{pmatrix} \quad (1)$$

The $TM_{td\leftarrow ui}$ is the transform matrix from the US image coordinate to the tracking device coordinate and the $TM_{w\leftarrow td}$ is the one from the tracking device coordinate to the world coordinate which is defined by electromagnetic tracker. (u_k, u_v) is the point coordinate in US image, s_x, s_y are the scale factors of x and y axis respectively, and (x_w, y_w, z_w) is the point coordinate in the real world defined by electromagnetic tracker. The probe calibration of US is to compute the $TM_{td\leftarrow ui}$.

Our research uses a 2-D alignment method to calibrate the probe[9]-[10].

D. Registration

Before the real-time tracking process, registration to map virtual space in the PC to the real-world space should be performed by using a landmark transformation which is rigid and in a least squares manner.

E. Navigation

After the preoperative planning, US probe calibration and registration are completed, the system enters a navigation stage, where the stent-graft is shown in the augmented realty environment of navigation system. As shown in the Fig. 3, the pink part is the target plane. The green model represents stent-graft. The navigation system will monitor the distance between the top point of stent-graft and the target plane and reports it in computer screen to guide the surgeon.

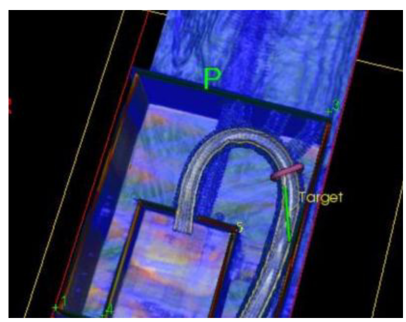


Fig. 3 The distance tracked by electromagnetic navigation system.

F. Components

Stent-Graft

The stent-graft(Fig. 4) is made of nitinol and sketches under normal temperature and can be folded in the ice water.

Catheter

As shown in the Fig. 5, the catheter has two sensors which are put into the front part of the catheter. The stent-graft is fold and embedded in the front of catheter between the two sensors so that the electromagnetic tracking system can track the stent-graft when the catheter was inserted into the aorta.

Fig. 4 The distance tracked by electromagnetic navigation system.

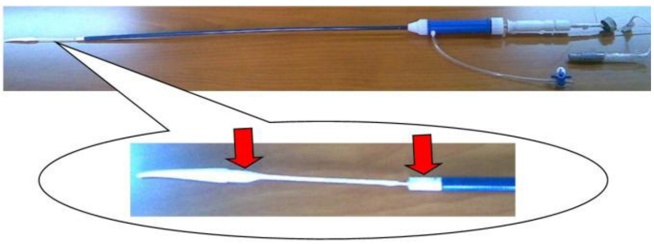


Fig. 5. The stent-graft used in this study.

Guide Wire and Cannula

A guide wire should be advanced from a common femoral artery access to the aortic arch. It is wrapped by a cannula, where three sensors are embedded (Fig. 6). The cannula can be tracked when it accesses to the aortic aorta. Based on the sensors' positions, a cardinal spline is employed to show the cannula model in the virtual reality environment. When the cannula arrives at aortic arch, it will be extracted, and the guide wire stays in the aorta and will guide the catheter move along it into the aorta.

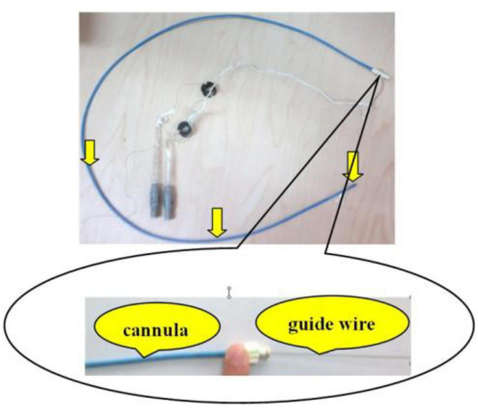


Fig. 6. The guided wire and cannula. The three yellow arrows indicate the location of sensors in the cannula.

Tracking Device

An Aurora electromagnetic tracking system (Northern Digital., Waterloo, ON, Canada) was used to track the pose of both the catheter and the US probe. For US image tracking, a custom-made sensor coil was mounted onto the US probe.

Software

We developed the software using Python 2.7, and makes extensive use of classes from free visualization toolkit: VTK 5.4 (www.vtk.org) and Atamai (www.atamai.com). It runs under Windows XP, on an Intel Core i5 computer with NVIDIA GeForce GTX 460 graphics card. A GE Vivid 7 US machine is used and the image is integrated into our navigation system after the probe calibration.

III. RESULT

In current stage, we had just finished a phantom study to validate our system initially.

A. Heart Phantom

In our validation experiment, the heart was represented by a heart phantom (Fig. 7a), which was made by transparent plastic glass. The small cube in the phantom simulates the heart chamber, and the bend pipeline simulates the descending aorta when the threaded pipeline simulates the esophagus. The corners of phantom were used as the landmarks in the fiducial marker based registration.

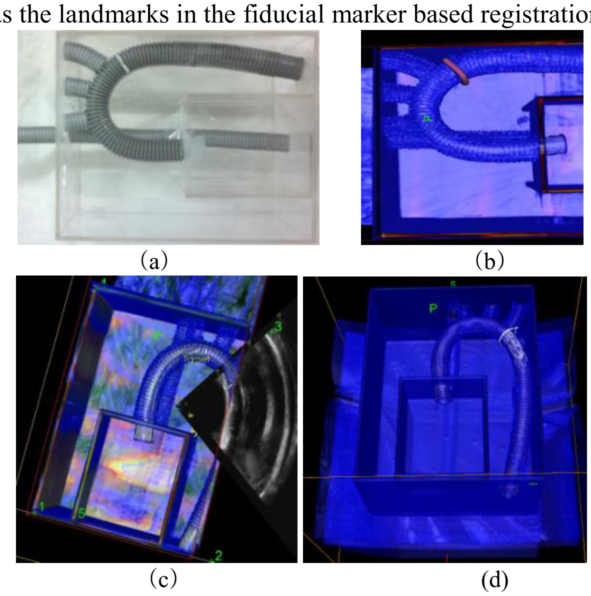


Fig. 7. The phantom study. (a) The phantom. (b) The preoperative planning result of phantom study. (c) Fuse the ultrasound image with preoperative CT model of the phantom. (d) A result of the stent-graft deployment in phantom.

B. Error

1) Fiducial Registration Error (FRE): it was assessed in each case by calculating the root mean square of the difference between the fiducial marks positions in image

space and their registered positions in the electromagnetic field . It is defined as:

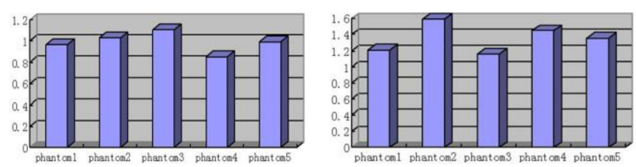
$$FRE = \frac{1}{N}\sum_{i=1}^{N}|Tx_i - y_i| \qquad (2)$$

where N is the number of source point, T is the transform between the electromagnetic field and preoperative CT image space. The fiducial registration is to find the T which minimizes the FRE. After the registration, the FRE can be reported from our system automatically.

2) Deployment error: it is defined as the difference between actual final stent-graft position and preoperative planning deployment position.

C. Phantom Experiment

A volume model and the preoperative planning was constructed from its CT image (Fig. 7b). After the probe calibration and registration were performed, the US image was integrated into the system (Fig. 7c). When the tracked catheter was inserted into bend pipeline, which simulated the aorta, the system can visualize the model of stent-graft embedded in the front of the catheter and show the distance between the center of the stent-graft and the target plane. When the distance shown in the system is close to zero, the catheter opened to release the stent-graft. Under the normal temperature of environment, the stent-graft unfolded and was deployed in the target position.



(a) (b)

Fig. 8. The result of phantom study. (a) FRE. (b)Deployment Error.

The FRE of the phantom study is 0.986±0.16mm(Fig. 8a). In order to measure the real deployment error, the postoperative CT image of the phantom was scanned, where the real distance between the stent-graft and the target position could be measured from the CT image. We performed the phantom experiment five times and record each deployment error in the Fig. 8b. The final deployment error is 1.354±0.175mm.

IV. CONCLUSIONS

This paper proposed a novel method which introduced the intra-operative US image and computer-assisted surgical navigation technique to help surgeon accomplish the Intra-cardiac Interventions surgery. The initial result is promising, and reveals that our method is possible used for the clinical application.

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