Intravascular Modeling and Navigation for Transcatheter Aortic Valve Implantation

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***Abstract*—This paper proposes a new vasculature modeling scheme based on the data fusion from intravascular ultrasound (IVUS) and electromagnetic (EM) tracking for Transcatheter Aortic Valve Implantation (TAVI). The system is suitable for obtaining inner cross section images of blood vessels, as well as capturing the corresponding pose of the probe from an electromagnetic sensor. Three-dimensional (3D) modeling of blood vessels is provided to facilitate intra-operative surgical guidance for the alignment of the artificial and native valves. A hybrid probe consisting of an IVUS sensor and an EM sensor has been integrated to capture data from both sensors simultaneously. An image processing method based on the gradient vector flow (GVF) snake method has been proposed, followed by the use of kinematic transformations to convert the image coordinates into 3D coordinates to reconstruct the anatomical model. The method could reduce the time of valve alignment, improve the precision for positioning, minimize the use of contrast agent and assess the status of deployed valve after surgery.**

I. Introduction

Aortic valve stenosis is characterized by the narrowing and obstruction of the valve between the left ventricle of the heart and the ascending aorta, leading to cardiac decompensation, chest pain and even sudden death. The standard procedure for surgical Aortic Valve Replacement (AVR) requires making a large incision by opening the chest, cutting off the ascending aorta from the heart, and using a cardiopulmonary bypass. This leads to significant trauma, long postoperative recovery time and a high mortality rate. Moreover, around 30% to 60% of patients cannot undergo this therapy, due to advanced age, left ventricular dysfunction, or the presence of multiple coexisting conditions [1].

To overcome these problems, the new technology of TAVI has been proposed to offer an alternative to minimize the trauma induced in traditional approaches [2]. The implantation procedure involves accessing a femoral artery and performing balloon valvuloplasty, followed by advancing a compressed bioprosthetic valve and then deployed by inflating the balloon on a catheter when reaching the native aortic valve. This new technology carries a significantly reduced mortality rate, with a mortality figure of 30.7% compared to 50.7% for the conventional standard treatment in one year [2].

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For TAVI, however, there are also several challenges associated with this new technology. For instance, the width of the native valve and its annulus is small. High or low valve placement relative to the native valve annulus will destroy the artificial valve or obstruct the coronary artery, leading to disastrous complications. Therefore, visualization and localization of the native valve annulus, and precise alignment and placement of the artificial valve on the correct location relative to this annulus is a crucial and time-consuming step. During the TAVI procedure, contrast enhanced C-arm fluoroscopy is usually used to provide intraoperative guidance. However, such technology can only provide 2D information for visualization of the complex aortic root, adding difficulties and consuming a considerable amount of time to locate and align the valve annulus. In addition, the contrast enhanced technique requires a significant amount of contrast agent, which can lead to adverse reactions due to its nephrotoxicity, especially to patients with kidney impairments [3]. Therefore, a more efficient technique for 3D vascular visualization and reduction in the use of contrast agent is desirable.

In recent years, intravascular ultrasound catheter imaging technology has been employed to obtain two-dimensional cross-section images of the blood vessels, providing anatomical information of the lumen morphology [4, 5]. This enables disease diagnosis with much less contrast agent compared to 3D angiography. It also permits the assessment of the interventions and evaluation of treatments after surgery. Vascular modeling technology based on IVUS has shown significant advantages for characterization of vascular diseases such as atherosclerosis [4]. It can also provide planning and navigation information for stent and stent graft deployment, as well as valve implantation.

Thus far, there is significant research in the use of IVUS for intra-operative guidance. For example, Sanz-Requena et al captured IVUS images by pulling back an IVUS catheter with constant speed of 0.5 mm/s and built a 3D reconstruction of artery models [6]. This method, however, is based on the assumption that the captured cross sections are parallel to each other. Therefore, it can be applied only to vessels with relatively small curvatures. Other groups have worked on the data fusion of IVUS and angiography [7-9], and estimated the pose of the IVUS probe tip in angiography images to obtain the approximate location of the IVUS images. However, the estimation of the pose of the IVUS probe remains difficult.

To overcome these limitations, we propose a new method

based on information fusion from both IVUS and electromagnetic motion capture sensors (MMCS). The purpose of this work is to provide 3D visualization of blood vessels based on the fusion of anatomical information obtained from IVUS with corresponding pose from an electromagnetic sensor. Such a method can be applied to the characterization of valve stenosis and surgical navigation, as well as the localization of the annulus for easy alignment and placement during valve implantation.

The proposed system has been validated on phantom data captured within a silicone model of the aorta. The 3D model of the phantom was reconstructed with this hybrid probe to evaluate the effectiveness of the proposed method.

II. Materials and Methods

A. *Hardware Configuration of Experimental Setup*

The hardware configuration of the proposed system is shown in Fig.1. The hybrid probe consists of an IVUS sensor and an electromagnetic sensor. The IVUS imaging probe of Volcano Catheter Visions PV 8.2 with a working frequency of 10MHz and a detection range of 60mm, was connected with the Volcano s5™ system (Volcano Corporation, CA, USA) to obtain the inner cross sections of the blood vessels. A mini electromagnetic sensor with 6 degrees of freedom (DOFs) was connected with the Aurora Electromagnetic Tracking System (NDI Corporation, CA) to collect the corresponding pose information.

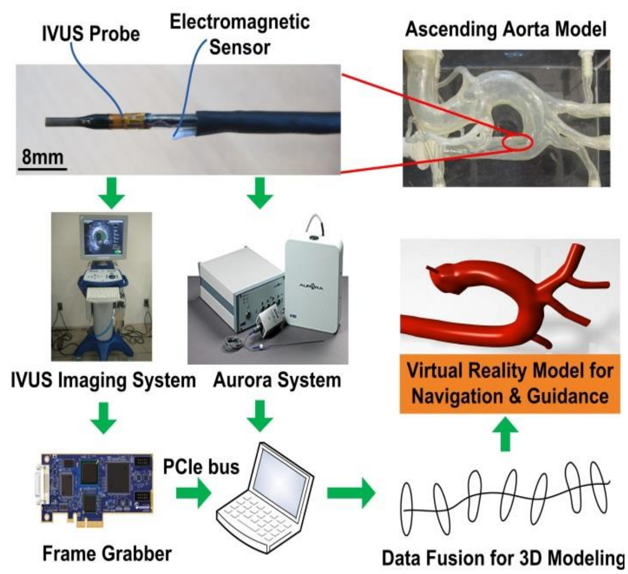

Fig. 1: The hardware configuration for the whole system. The hybrid probe consisting of two sensors is shown on the top left.

A DVI2PCIe frame grabber was connected with the IVUS Imaging System to record video data of the cross sections of blood vessels at 20 frames per second (fps). The corresponding pose information was recorded at the same frequency simultaneously.

A silicone-based, transparent, anthropomorphic phantom (Elastrat Sarl, Geneva, Switzerland) representing an ascending aorta was applied for this study, shown in the right top in Fig.1. Such a membrane model is suitable for evaluating the proposed method. This silicone model was immersed into a water tank and no flow was circulated inside it during imaging with the hybrid probe.

B. *Image Processing for Extracting Coordinate of Contour*

A sample video frame with a resolution of 1280 x 1024 pixels captured from the IVUS imaging system is shown in Fig.2. The IVUS probe appears as a hollow and circular shape in the center of the region of interest (ROI) ROI1. The ROI of ROI2 shows the cross section of the blood vessel. The scale in the 2D images is presented by the distance between the blue markers, and is equal to 5mm in our experiment.

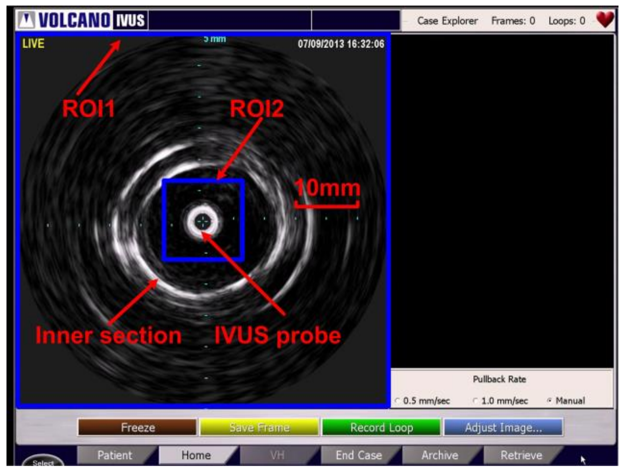

Fig.2: A video frame captured from blood vessel cross section

According to the properties of the captured images, a new image processing method has been implemented. The main steps of this process can be listed as follows.

Step 1: Obtain an IVUS video frame and the corresponding pose of the hybrid probe from the two sensors

Step 2 : Determine the center of the IVUS probe:

Select the ROI1, convert it into grey scale, apply a median filter, then perform Hough Circle transform in ROI1 to calculate the IVUS probe center location O_I and the radius r_1 for the circular black area in the center and estimate the radius r_2 of the white points (noise) surrounding r_1

Step 3: Pre-processing for Canny algorithm:

Select ROI2, convert it into grey scale, remove the image part of IVUS probe and the surrounding noise by drawing a black solid circle centered in O_I with radius r_2 and then apply the an average filter to remove the scale markers and the remaining noise

Step 4: Apply the Canny edge detection algorithm to obtain the rough contour of the cross section captured from the blood vessel model, and remove the scale makers and noise inside the inner cross section according to their length information

Step 5: Create a circle centered in O_I with radius r_3 , equal or larger than r_2 as an initial contour, and apply the Gradient Vector Flow (GVF) snake [10] to obtain a continuous and smooth contour

Step 6: Calculate the kinematics to convert the image coordinates of the contour into 3D coordinates

Step 7: Create a point cloud from the anatomical and pose information, mesh and render it into a 3D model.

C. *Kinematics for Converting Image Coordinate into 3D Global Coordinate*

Then, we need to calculate the pose for each contour and convert the contour points into 3D coordinates. Fig.3 shows the relationship of the coordinate systems among the Aurora emitter, the electromagnetic sensor and the IVUS emitter. The kinematic transformation can be expressed as:

$$^{O}T_{I} = {}^{O}T_{M} \cdot {}^{M}T_{I} \qquad (1)$$

$$^{O}P_{I} = {}^{O}T_{I} \cdot {}^{I}P_{C} \qquad (2)$$

where, $^{O}T_{M}$ stands for the transformation between the electromagnetic tracker and the Aurora coordinate system. There are seven parameters $T_x, T_y, T_z, Q_0, Q_x, Q_y, Q_z$ acquired from the electromagnetic sensor. The first three parameters represent the position, and the others are used to express the orientation using quaternion conventions. The quaternion information is converted into a transformation matrix to obtain $^{O}T_{M}$. After the assembly of the hybrid probe, these two sensors share the same orientation. $^{M}T_{I}$ expresses the transformation matrix between the electromagnetic sensor system and the IVUS emitter coordinate system, and it can be measured directly.

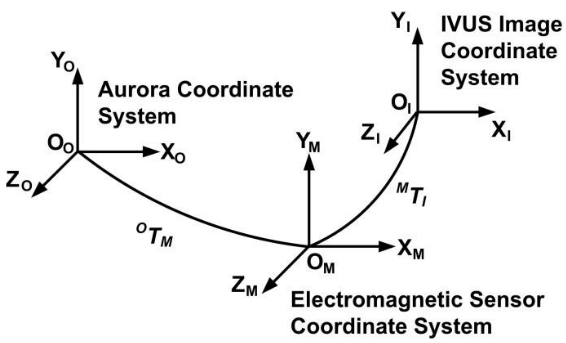

Fig.3: Kinematic relationship among Aurora emitter, Electromagnetic sensor coordinate and IVUS emitter coordinate systems

To transform these coordinates from pixels to millimeters, the following equation is used:

$$^{I}P_{C}(X_P, Y_P, Z_P, 1) = P_C(k * \Delta x, k * \Delta y, 0, 1) \quad (3)$$

where, Δx and Δy stand for the coordinates of the contour relative to the image center in pixels. *k* expresses the real distance in millimeters that every image pixel stands for, and can be obtained from the image processing for the scale marks on the raw image. In our experiment, it is equal to 0.077 mm/pixel. $^{I}P_{C}$ represents the pixel coordinates expressed in millimeters, and uses the homogeneous coordinate format for convenience for the kinematic transform.

After obtaining these parameters, we can calculate $^{O}T_{I}$ and multiply it with $^{I}P_{C}$ in (3) to calculate the 3D physical coordinates according to equations (1)-(2). $^{O}P_{I}$ expresses the coordinate of a pixel on the contour measured in millimeters in the global coordinate system.

III. RESULTS

A. *Image Processing for Extracting and Locating Coordinate for Contour*

The results of *Step 2* to *Step 5* of the image processing are shown in Fig.4. The radius r_2 was calculated as 70 pixels. A circle with a larger radius was used as the initial contour in *Step 5*, and the contour result shown in blue was obtained after applying the GVF snake. This algorithm runs at about 0.2 fps on an Intel(R) Core(TM) i5-2520M @2.5 GHz with 4 GB RAM.

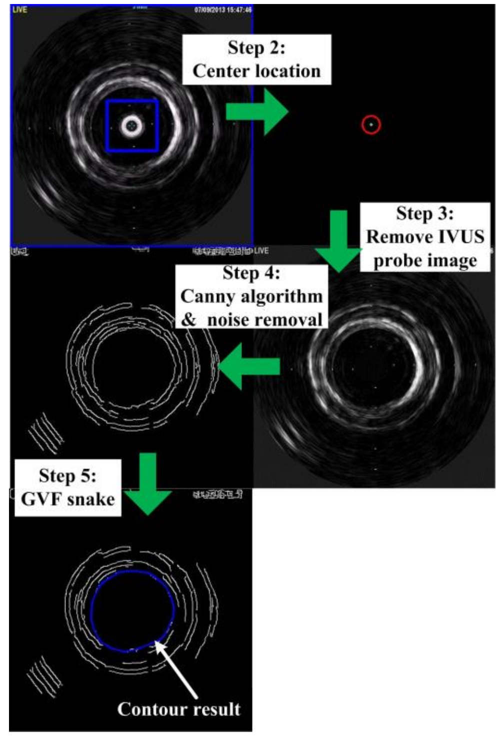

Fig. 4: Image processing for IVUS images

B. *Data Fusion for 3D Modeling*

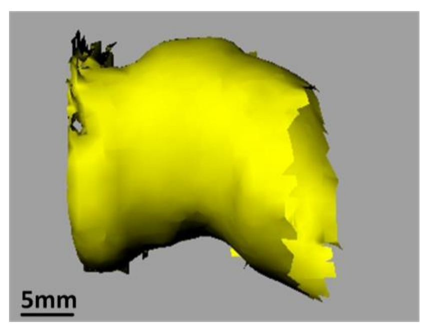

Fig. 5: 3D modeling for part of descending aorta based on sensor fusion method

The integrated probe was used to scan inside the descending aorta to collect data. After applying *Step 6* and *Step 7* in the image processing method, the 3D structure of the blood vessel can be reconstructed. The preliminary modeling for part of descending aorta is shown in Fig.5. A complete scan inside both of ascending and ascending aorta will be conducted in the near future.

IV. DISCUSSION

In this work, we have proposed a system to obtain the inner cross sections of blood vessels and capture the corresponding catheter pose for locating these cross sections. The 3D reconstruction of the blood vessel can provide both morphological information and relative position information

between the blood vessel and the catheter tip. This can assist the surgeons to manipulate and advance the deployed devices within the blood vessel. During the alignment and valve placement in TAVI, the 3D reconstruction of the vessels can support precise localization and easy observation of the valve stenosis and annulus. Therefore, the hybrid probe can be used as a visualization aid to improve the efficiency in the implantation of artificial valves. After image registration, the virtual environment can be used to provide morphological information and navigate the operations of surgical tools, facilitate the implantation in the following steps. This method can support the use of non-contrast enhanced imaging and prevent reinjection of contrast media, reducing the use of contrast media.

The proposed image processing method is simple and fully automatic, advancing previous works which require the manual selection of the initial contour to converge to the real contour. Besides, when the IVUS probe is near to or comes in contact with the inner cross section, parts of the contour will converge on the IVUS probe image, leading to incorrect contour estimations. Our method has been proven to solve this problem.

This integrated sensor can be also deployed as an assessment tool to evaluate the status of the deployed valve after surgery. Misalignment of the implanted valve will cause valve migration, an important complication after the TAVI procedure. This would result in moderate and severe aortic regurgitation, which is one of the most important predictors of mortality and can cause serious consequences [11]. This technology can provide essential information for surgeons to take precautions in advance. It can also be applied to abdominal aortic aneurysms and thoracic aortic aneurysms. The proposed visualization framework can provide 3D modeling of the blood vessels and facilitate the location of branches to improve the efficiency in the installation of stent graft on the secondary branches of blood vessel for these two diseases.

The disadvantage of this system is that the IVUS probe and electromagnetic sensor are assembled in series with around 10 mm distance between them. When the catheter is confronted with large forces, the coordinate relationship between the two sensors will be affected by deformation. This issue could be tackled by estimating the deformation using force feedback from sensors installed in the affected area. If the surgeon can insert the integrated sensor with a relatively slow velocity away from the vasculature walls, such obstacle and deflection can be neglected.

In the future, additional electromagnetic sensors will be attached along the IVUS probe to estimate its shape [12] and realize Simultaneous Catheter and Environment Mapping (SCEM), which can provide both catheter localization and vessel geometry reconstruction. This would provide 3D visualization imaging of the artificial valve with respect to the stenosed valve for precise alignment.

V. Conclusion

A practical solution for 3D intravascular modeling of the aorta has been proposed based on the sensor fusion between images from an IVUS imaging probe and pose information from an electromagnetic sensor. An effective image processing pipeline was proposed to realize fully automatic processing of IVUS images. Experiments were carried out in an in-vitro environment to evaluate the effectiveness of proposed method. It should be noted that the current implementation of the IVUS image processing algorithm is not yet real-time because of the computational complexity of the GVF snake method. Our future work will focus on the improvement of the hardware platform, the IVUS image processing algorithm and the 3D surface modeling to enable real-time processing, as well as the evaluation of the modeling accuracy.

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