Computerized Medical Imaging and Graphics 37 (2013) 150–161

Contents lists available at SciVerse ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

Automatic and efficient contrast-based 2-D/3-D fusion for trans-catheter aortic valve implantation (TAVI)

Rui Liao*, Shun Miao, Yefeng Zheng

Imaging and Computer Vision, Siemens Corporation, Corporate Technology, Princeton, NJ, USA

ARTICLE INFO

Article history:
Received 28 March 2012
Received in revised form
21 December 2012
Accepted 23 January 2013

Keywords:
Image-guided intervention
2-D/3-D registration
Contrast agent inflow detection
Minimally invasive procedures
Trans-catheter aortic valve implantation

ABSTRACT

Trans-catheter aortic valve implantation (TAVI) is a new breakthrough in the field of minimally invasive surgery applied on high-risk patients with aortic valve defects. 2-D X-ray angiographic and fluoroscopic images are typically used to guide TAVI procedures, for which contrast agent needs to be injected from time to time in order to make the anatomy of the aortic root visible under X-ray. Advanced visualization and guidance technology involving patient-specific 3-D models of the aorta can greatly facilitate the relatively complex TAVI procedures by providing a more realistic anatomy of the aortic root and more accurate C-Arm angulation. In this paper, a fully automatic and efficient system for contrast-based 2-D/3-D fusion for TAVI is presented. Contrast agent injection into the aortic root is automatically detected based on histogram analysis and a likelihood ratio test on the X-ray images. A hybrid method is then applied for contrast-based 2-D/3-D registration between the 3-D model and the detected angiographic frame. By integrating the information of aorta segmentation and aortic landmark detection into intensity-based registration, the proposed method combines the merits of intensity-based registration and feature/landmark-based registration. Experiments on 34 clinical data sets from TAVI patients achieve 100% correct detection on the contrast-enhanced frame, and a mean registration error of 0.66 ± 0.47 mm for 2-D/3-D registration. The proposed method is furthermore highly efficient with an average processing time of 2.5 s after the most contrast-enhanced frame is available, demonstrating the efficacy of the proposed method to be adopted in a clinical setup.

1. Introduction

Aortic valve disease is affecting 1.8% of the global population and is the most frequent heart valve disease in developed countries. There are about 60,000 surgical aortic valve replacements every year in Europe and even more in the United States [1]. Although open heart surgery is a well-established procedure with a proven success rate, one-third of TAVI candidates are denied surgery, particularly in the elderly, because of a perceived high operative risk. Compared to traditional open surgery, trans-catheter approaches deliver the prosthetic valve via a small incision at the patient's chest or groin. It is best-suited for high-risk patients with severe aortic stenosis, and has the potential to be applied to regular-risk patients in the future. TAVI has already accounted for more than 20% of aortic valve replacement procedures in Germany. It is also expected to grow fast in the United States in the coming 2–3 years after the recent FDA approval for commercial use of the Edwards SAPIEN valve [2]. Furthermore, the recent randomized trials show that TAVI significantly reduces the mortality rate for patients who are denied surgery, compared to the current standard medical therapy, and has a comparable outcome to open heart surgery for high-risk patients who can undergo surgery [3].

During TAVI procedures, X-ray angiographic and fluoroscopic imaging is routinely used to guide the operation, because the visibility of the target area is limited to the naked eyes due to the small incisions. However, fluoroscopic images do not display the anatomic structures without the contrast agent, which on the other hand needs to be minimized for patients' safety. Recently, 3-D models were introduced to support TAVI procedures by overlaying the 3-D aortic model onto fluoroscopy. Introduction of the patient-specific 3-D model of the aortic root has the advantages of displaying more realistic anatomical details and providing more automatic and accurate C-Arm angulation for optimal valve deployment [4]. The 3-D aortic model can be derived from pre-operative high-resolution computed tomography (CT) and magnetic resonance imaging (MRI) volumes, or from an intra-operative C-Arm CT volume [5].

In this paper, a fully automatic and highly efficient system for 2-D/3-D fusion of the 3-D model and angiography/fluoroscopy during TAVI procedures is presented. The whole system consists

* Corresponding author. Tel.: +1 609 734 3375; fax: +1 609 734 6565.
E-mail address: rui.liao@siemens.com (R. Liao).

0895-6111/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compmedimag.2013.01.008

of C-Arm CT acquisition and reconstruction, automatic 3-D aorta segmentation and landmark detection on the C-Arm CT volume, optimized volume visualization and derivation of the optimum C-Arm angulation, and 2-D/3-D fusion for navigation and guidance. The focus of this paper is automatic contrast-based 2-D/3-D registration between the 3-D model and 2-D angiography, to compensate for motions such as patient movement and aortic root movement due to the insertion of the devices. Contrast agent injection into the aortic root is automatically detected on X-ray images based on the method presented in [6,7], and the positive response to contrast agent inflow detection is then used to automatically trigger 2-D/3-D registration between the 3-D model and the angiography showing the aortic root [8]. A seamless workflow and accurate registration between the pre-operative 3-D model and the patient undergoing the procedure are the key components for a successful image guidance system for TAVI, which is a relatively complicated procedure involving a large number of staff, equipment and steps [2–5].

Techniques for 2-D/3-D registration between 3-D volumes and 2-D X-ray images can be divided into two general groups: landmark/feature-based methods and intensity-based methods. Landmark/feature-based methods [9–11] register landmarks and/or salient features that have been extracted automatically or semi-manually from both the 2-D image and the 3-D volume. While this approach exhibits fast execution time and high robustness in the face of large initial misalignment, it is difficult to achieve full automation, especially for salient feature extraction from 2-D X-ray images that inherently suffer from overlapping and/or foreshortening due to 2-D projections. For intensity-based registration algorithms [12–14], simulated X-ray images are produced from the 3-D volume, and are referred to as digitally reconstructed radiographs (DRRs). The translation and rotation of the 3-D volume are estimated through an optimal match between the DRRs and the X-ray image. While intensity-based methods have been shown to give substantially more reliable results than their feature-based counterparts, its accuracy may be sub-optimal at the structure of interest, and its performance is seriously deteriorated when there is mismatch between the contents shown in the 2-D and 3-D data.

This paper describes a hybrid method that incorporates the segmentation and landmark information of the 3-D aortic root into intensity-based registration, for a highly accurate and robust 2-D/3-D alignment of the aorta. Both the 3-D volume and the 2-D images are captured with contrast agent showing the patient's aortic root. 2-D angiographic images are first pre-processed to remove the background and/or devices such as the catheter and TEE probe. 3-D aorta segmentation and coronary ostia landmark detection is performed on the 3-D volume using the learning-based method presented in [5]. The segmented aorta and detected landmarks are given inputs to our algorithm. Discussion on the accuracy of the segmentation step is out of the scope of this paper, and readers are referred to [5] for more details. Aorta segmentation is then used to produce clean DRR images that show only the aorta and excludes all the peripheral structures such as the spine. Landmarks representing the left and right coronary ostia are further utilized in an integrated fashion with the intensity-based method. A multi-layer and multi-resolution optimization strategy is finally deployed to find the optimal registration.

The remainder of the paper is organized as follows. A brief overview of the image-guided system for 2-D/3-D fusion during TAVI is given in Section 2. Methods for efficient and accurate contrast-based 2-D/3-D registration between the 3-D model and the angiography are covered in Section 3. Experiments are performed on a large number of clinical datasets and the quantitative results are reported in Section 4. We then conclude with Section 5 for discussion and future work.

2. Overview of image-guided system for TAVI

Previous work on computer-based support for TAVI includes the modeling for procedure planning [15,16], guidance by tracking the prosthetic valve in fluoroscopic images [17], a robotic system using MRI imaging [18], and fusion between ultrasound and fluoroscopic images [19]. The goal of our fusion system is to provide image guidance based on interventional C-Arm CT volumes to add detailed 3-D information that is helpful for an accurate navigation and deployment of the prosthetic valve. The system needs to be set up in the complex environment of a hybrid operating room and used by a physician during TAVI procedures without additional support from the control room. Therefore, it is crucial for the acceptance of such a system to be fast, to minimize user interactions, and to allow table-side control. We give a brief overview of the proposed system here, though a more detailed description of our prototype system that is currently under clinical trial can be found in [4].

Right before placing the implant, an interventional 3-D C-Arm CT volume of the aortic root is obtained by acquiring a rotational 2-D image sequence of 200° over 5 s on the C-Arm system [20]. The rotational run is then reconstructed based on a software available with the C-Arm system [21], which takes about 12 s. The aortic root is then segmented and eight landmarks are detected from the reconstructed C-Arm CT volume using the method in [5]. This step is automatically triggered after a valid aortic C-Arm CT volume is reconstructed, and is fully automated and very efficient, taking about 2.5 s on average. The eight landmarks include the lowest point of each aortic root cusp (hinge points), the coronary artery ostia, and the commissure points where the cusps meet. Additional structures/measurements and subsequently the optimum C-Arm angulations are then automatically derived from the segmentation of the aorta and the detected landmarks. In particular, we derive a circle parallel to the plane spanned by the three hinge points, and an optimal C-Arm angulation for valve implantation is achieved when this circle degenerates to a straight line (Fig. 1). Optimized visualization of the aortic root is further automated as outlined next, which takes less than 1 s on average. The last step of the image guidance system is 2-D/3-D overlay of the 3-D model onto the fluoroscopic/angiographic live images for online monitoring and navigation. A flowchart for all the steps supported intra-operatively using our prototype system is given in Fig. 2.

Volume rendering of the 3-D model is optimized using a learning based method, which learns the optimal rendering parameters from training examples that are manually adjusted by an expert for an optimized visualization. In particular, the appropriate volume rendering parameters c_{opt} for the transfer function center and w_{opt} for the transfer function width are calculated automatically based on the voxel intensities:

$$\begin{aligned} c_{opt} &= f_{c,in} m_{in} + f_{c,out} m_{out} + f_{c,offset} \\ w_{opt} &= f_{w,in} m_{in} + f_{w,out} m_{out} + f_{w,offset} \end{aligned} \tag{1}$$

Here, m_{out} (m_{in}) is a patient-specific value and is determined by the mean intensities of all the voxels outside (inside) the boundary of the segmented aortic root with a fixed distance to it. The underlying set of voxels is computed using the morphologic operators of dilation and erosion with a certain number of iterations. The six parameters $f_{c,in}, f_{c,out}, f_{c,offset}, f_{w,in}, f_{w,out}, f_{w,offset}$ in Eq. (1) are fixed values that are obtained by a training sample set of segmented volumes. For each of these training volumes we manually adjust optimal window width and window center values. Together with the calculation of the corresponding values m_{in} and m_{out} we get an over-determined system of linear equations with six unknown parameters, which are then solved by a least-square fitting method.

When overlaying the 3-D model onto a live fluoroscopic image, we offer the options of volume, mesh, and contour view of the