3D Reconstruction of Coronary Arteries from Angiographic Images: A Survey

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Abstract

X-Ray angiographyis considered to be the **"**golden standard**"** of all times in the medical imaging field due to its wide range of applications. In this paper, a survey is performed on the basic techniques and the methodologies that have already been proposed by various researchers in the field of 3D reconstruction of coronary arteries using one or more angiograms as in monoplane or biplane angiographic systems or a volume of data as in rotational angiographic systems. Also, the various procedures that need to be performed are stated and described showing the contribution of each step in the reconstruction process. These procedures include distortion correction, motion compensation, feature extraction, background removal, projection geometry optimization and topology identification, surface visualization etc.

Keyword : *3D Reconstruction, Centerline Extraction, Motion Compensation, X-Ray Angiography*

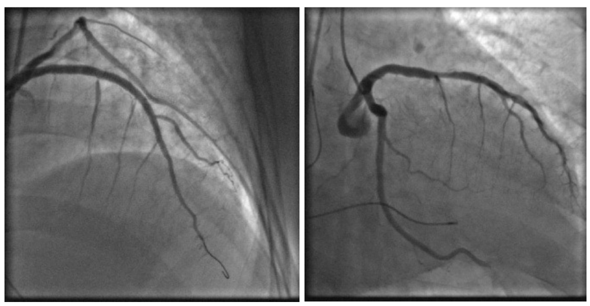
1. Introduction

X-Ray angiography is defined as a medical imaging technique that is used to envision the inner structures of the blood vessels and other human body parts with a major focus on the veins, arteries and human heart chambers. The basic procedure involves injecting a radio-opaque contrasting agent into the blood stream and using imaging techniques based on X-ray to get the inner view of the human body. This technique is a major approach in present day in identifying coronary artery diseases (CAD). Coronary artery diseases or atherosclerotic heart diseases are the most common cause of heart attacks nowadays. These diseases are caused by building of plaque on the inner walls of the arteries which leads to their narrowing and thus results in restriction of blood and oxygen flow to the human heart. This causes heart attacks and heart failures in the long run. Fig.1 shows the angiogram, and their 3D reconstruction respectively [19].

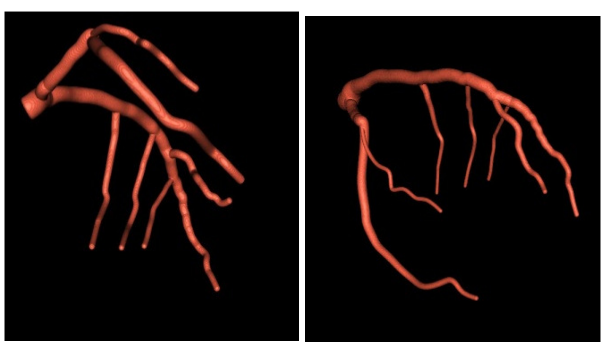
In the last decade, several techniques have been developed to assist physicians in diagnosis and treatment of CADs. They include magnetic resonance angiography (MRA) [1], computed tomographic angiography (CTA) [2] and 3D ultrasounds [3]. But all of them encounter some or the other limitation due to which X-Ray angiography emerges as a golden standard of all times for such purposes. However, due to 2D projection of the X-Ray instruments, a huge amount of information is lost about the coronary arteries. Moreover, qualitative analysis of diseases like arteriovenous malformation (AVM), atherosclerosis and aneurysm suffer from certain limitations as: Firstly, in 2D projections, overlapping and foreshortening are very common phenomena which can be corrected only by the experience of the physician. Thus anybody who does not have much background information wouldn't be able to correlate information obtained by the 2D projections taken from different viewing angles and will remain subjective to the visualization of the doctor. Also, a major drawback is encountered due to the mechanical limitation of the instruments being used for imaging.

The imaging angles are restricted by C-arm even in the advanced rotational angiographic systems due to which the clinicians cannot reach all the desired angles of projection. Thirdly, the most commonly used monoplane angiographic systems provides one angiogram from one angle and it is very difficult for a novice doctor to visualize the actual state of the disease with this limited information. In order to get more elaborative information, the patient has to undergo several iterations of the same procedure through different viewing angles. This increases the level of exposure to radiations and higher quantity of contrasting material injections for the patients.

Due to the above mentioned drawbacks of some of the imaging techniques, 3D reconstruction of the coronary arteries and interested vessels has attracted attention of several researchers. The 3D reconstruction of the vessel not only empowers the physicians with an insight to the internal condition of the patient but also helps him to visualize a particular part of the vessel in detail and from different viewing angles without exposing the patient to harmful radiations or insertion of the contrasting agent. This paper presents a survey about the techniques that have already been proposed in the field of 3D reconstruction of coronary arteries and also takes into consideration the methodology that is generally adopted in order to achieve this reconstruction. The section II summarizes all the related techniques that have already been proposed in this field and the basic categorization of these approaches. Also it describes the basic methods that have already used in this field. Then the following section III describes the basic issues or the basic concerns of the reconstruction procedure like motion compensation, curve matching, background removal etc. Thereafter, the section IV gives the conclusions about these described techniques and the improvements that can be done to these procedures.



(a) (b)



(c) (d)

Fig.1 The 3D reconstruction of the coronary artery from an angiogram. (a) and (b) shows the angiographic images while (c) and (d) shows the 3D reconstruction of (a) and (b) respectively.

2. Related Work

Over the last two decades, several methods and techniques have been proposed for the reconstruction of coronary arteries in 3D plane using two or more than two angiographic images. These techniques and approaches can be distinguished into two major categories on the basis of two different views. Firstly, on the basis of geometric model being used for reconstruction- This category, basically, defines the kind of approach being used for the reconstruction and can be classified as:

Top-down method- the vessel segment is usually constructed as parameterized deformation model that evolves under the constraints of the combination of internal and external energies in 2-D projection images. Thus, the vascular structure in 3-D space adapts its structure to a stable representation, which has minimum projection errors in all projections. This method avoids the calculation of correspondences and is therefore more flexible than the bottom-up method. The deformable model was first proposed by Terzopoulos et al.

1. [25,26] in the 1980s and was initially utilized to perform elastic deformation, including viscoelasticity, plasticity, and 3-D model fracture. The basic advantage of this approach is that calculation of correspondence of every feature point on the vascular structure is not required but the images should be obtained at the same cardiac cycle to avoid elastic warping among different parts of vasculature.

2. **Bottom-up method**- Correspondences among the acquired images are constructed by extracting the terminals of vascular features and the bifurcations. Then the direction vectors, connections and diameters are acquired from the topology structure present in the 2D angiograms. Also, artifacts and distortion in the obtained images has to be corrected so that the correct geometric relations can be reflected. Thereafter, a 3D vasculature model is constructed based on the matched vascular segments. Blondel*et al.* [14] reconstructed coronary arteries using a single-rotation X-ray projection sequence. The correspondences in their work were determined by integration of external and internal energy terms, and the correspondences obtained from the two views are re-projected to a third view for refining the 3-D structures. Chen *et al.* [5] used imaging parameters to construct the initial geometric relationship between two views. They optimized the vasculature by minimizing the re-projection errors of centerline points and the vector angle of vascular branches using this relationship. Messenger *et al.* reconstructed the coronary arteries of more than 40 patients using the method proposed in [6]. The accuracy of 3-D reconstruction for this method is correlated with the correspondence results. One major problem is the possible intersection of the epipolar line with multiple vascular segments. It causes difficulty in finding the actual correspondence, especially when the vessel segment is overlapped or in parallel with the epipolar line. Hence, topological information is crucial for correspondence optimization. Also, user interaction is generally involved in correspondence determination, which is

time-consuming and may introduce large errors for 3-D reconstruction.

The second basis of classification is on the basis of usage of the angiographic instrument- This category is basically classified on the imaging characteristics on the instrument itself. The different categorization could be monoplane systems, biplane systems or the rotational systems.

1. **Monoplane systems-** In case of monoplane systems, one view of the coronary artery are focused at a particular time. This method is still widely used of the 3D reconstruction and is considered as the "golden standard" in medical imaging[4]-[9].

2. **Biplane systems-** In this case, two or more predefined stationary views, at different angulations around the patient are taken for both left and right coronary arteries at an instance[10]-[13].

3. **Rotational systems-**Here, CT like volume of data is acquired by rotating the C-arm around the patient and from the obtained series of X-Ray images,those with the same cardiac phase are selected for the reconstruction process [14]-[18][20].

Radeva [10] andCañero [11] used deformable models for constructing the coronary branches for resolving the issues related to correspondence points matching. Movassaghi*et al*. [9] presented a quantitative analysis of 3-D coronary modeling from two or more projections. Although Radeva, Cañero and Movassaghi adopted the calibrated method, neither of them accounted for table movement when they estimated the transformations among different views. Chen and Carroll *et al*. [5]–[7] used bifurcations and direction vectors of the vessel as data input to optimize the transformation parameters of the C-arm, but they did not take geometrical distortion into account. To resolve this, Jian*et al.* proposed a novel approach, on the basis pinhole camera model and already existing optimization methods, to nonlinearly optimizing and refining the 3D structure of the vessel skeletons that took into consideration the table movement and problems associated with the body movements of the patient [19]. Andriotis et al. [22] proposed a method that combined image enhancement, automatic edge detection, an iterative method to reconstruct the centerline of the artery and reconstruction of the diameter of the vessel by taking into consideration foreshortening effects.

3. Methodology

Fig.2 shows the basic flowchart of the reconstruction procedure. The basic methods that are used in the 3D reconstruction of coronary arteries are as follows:

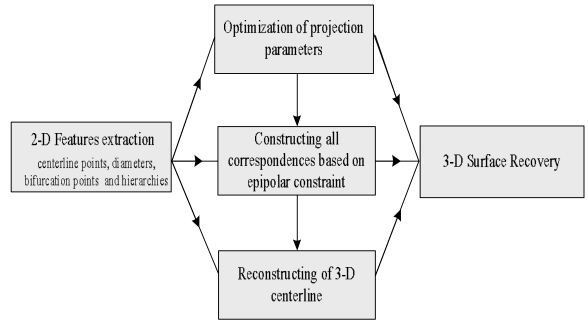


Fig.2 The basic procedure of 3D reconstruction

A. Distortion Correction or Preprocessing

This phase of the reconstruction is a very critical part as the motion due to the cardiac and respiratory movement is addressed in this phase. Along a particular cardiac cycle, systole is described by myocardium contraction and a top-to-bottom motion of the coronary tree in the axial direction. Following systole is the diastole that is described by myocardium relaxation and bottom-to-up motion of the coronary tree in the axial direction. In addition to this cardiac motion, the medical imaging techniques have to compensate respiratory motion due to which coronary arteries are subjected to a vertical translational in the axial direction. These motions leads to distortion in the images obtained through angiography. So, this distortion needs to be corrected before using these images for the reconstruction procedure. Fig.3 shows the distortion correction by designed grid phantomacquired with X-ray angiographic imaging device [17].

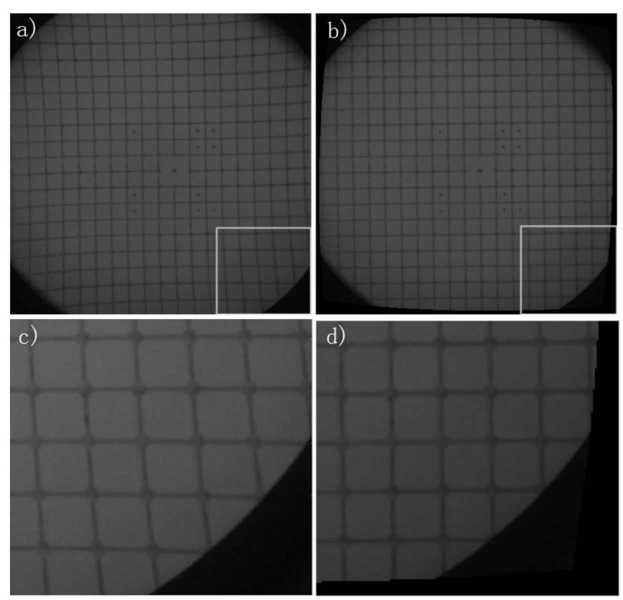


Fig.3 Distortion correction for the angiographic image: (a) is the original image, (b) is the corrected image, and (c) and (d) correspond to the block in (a) an d (b).

B. Background Removal and Vessel Enhancement

The angiographic images consists not only the vessels of interest but also several background structures. In some cases, these structures are not visible in all the views because the field of view is smaller than the patient's torso. So if not removed before reconstruction, they can induce truncation artifacts. So, many researchers apply subtraction techniques to projection data formed only by the arteries. A mask image is required to perform the subtraction and is obtained by processing the angiograms. So, the interested vessel is then enhanced after the background removal. When the interested vessel is enhanced, several other uninterested vessels also get enhanced in the angiograms called the pseudo vessels that have to be removed in order to get the qualitative reconstruction of the actual coronary arteries.

C. Feature Extraction and Topology Identification

The vascular feature extraction and topology identification are very important for computer-aided diagnosis and treatment of vascular diseases. Currently, manual operation is still the most commonly used method for vascular structure extraction in clinical practices. The extraction of centerline, diameter and bifurcation points empowers the researchers to automatically generate vascular structures in 3D plane. The centerline extraction procedure includes locating the starting position of the centerline, then the seed points are determined and tracking is performed. Also the false vascular parts are removed in the final stage. Diameter of the vessel being analyzed and the location of the bifurcation points play a very crucial role in the reconstruction procedure.

D. Projection Geometryand Optimization

Generally, the acquisition principle of X-ray angiography is similar to the pinhole camera model used in computer vision. Based on this model, the projection of a 3-D world coordinate X to the 2-D image coordinate x can be described by a projection matrix P:

$$x = \lambda_i P_i X \ , P_i = K_i \left[R_i \middle| \ t_i \right], i = 1,2 \qquad (1)$$

where and are the image and world coordinates in homogenous form respectively, is the homogenous scale factor which is dependent on . and are rotation matrix and translation vector respectively, which represent the rigid transformation from world to the angiographic coordinate system and generally named as extrinsic parameters. is the intrinsic matrix and can be written as:

$$K_i = \begin{bmatrix} \frac{SID_i}{\alpha_x} & \frac{SID_i}{\alpha_y} \cdot s & x_c \\ & \frac{SID_i}{\alpha_y} & y_c \\ & & 1 \end{bmatrix} \qquad (2)$$

where is the source to isocenter distance of the -th view. and are image pixel spacing in the and directions of the image coordinates respectively, is referred to as the skew parameter, is principle point.

However, in real clinical scenarios Eq.1 cannot accurately represent the projection geometry because of:

a) Distortion of the imaging axis due to the image intensifier.
b) Due to installation errors in the mechanical devices.
c) Table movement which commonly happens during angiographic procedures which introduces complicated motion of the imaging chain.

So some optimization needs to be performed in order to compensate this distortion in the projection geometry. After initial estimation of the structure of the bifurcations and the motion of the angiograms, it is necessary to perform a global optimization. The main concern of the optimization procedure is to reduce point transfer error and the algebraic transfer error. Point transfer error is the error observed in the Euclidean image distances between the extracted skeleton points and corresponding back projections of the reconstructed 3-D centerline points on the two images. The algebraic transfer error is the difference between the 2-D direction vectors and those of the back projections of the reconstructed 3-D direction vectors on the two images.

E. Surface visualization

The 3D and 2D information obtained from above procedures along with the transformation parameters of the two views can be utilized to reconstruct the surface of the vascular tree. Most of the already done studies, used circles to fit the cross sections of the vessels which was a straight forward approach and only used information from one view of projection[5]-[8]. But the basic drawback was that most of these studies did not considered the fact that the projections that were used for the calculation are not perpendicular to the normal of the cross section planes of the vessels. It results in reduced accuracy of the fitting calculation. However, some researchers used both views to fit an ellipse to the cross section [9], the intersection points were considered to be coplanar but were not consistent with the real life scenarios. Fig.4 shows an example of the triangular surface rendering of a reconstructed bifurcation.

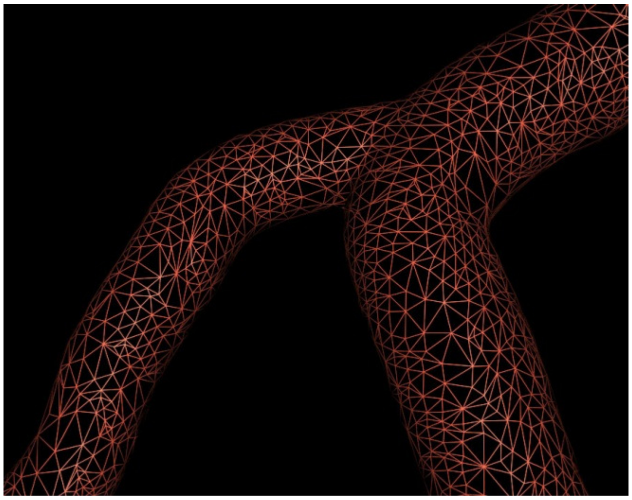


Fig.4Triangular surface rendering of a local bifurcation of the reconstructed vascular tree model.

4. Conclusion

This paper has put forward the basic methodologies that have already been proposed by different scholars in the last two decades for 3D reconstruction of coronary arteries by one or more angiograms. It also establishes the basic necessity of 3D visualization of the coronary artery in spite of the fact that several other medical imaging techniques are available and are being widely used. But the basic advantage of using 3D reconstruction is that it envisions the physician about the 3D model of the coronary artery to better visualize the actual state of the patient.

All the techniques like preprocessing of the data, vascular enhancement, feature extraction etc. are elaborated and the already existing techniques proposed for these procedures are stated. Several kinds of data like monoplane or biplane or huge volumes of data from rotational angiograms are used for the reconstruction process.

Thus, it can be shown through the above survey that 3D reconstruction has emerged as a very powerful tool of medical imaging.

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