TOWARDS COMPUTER ASSISTED CARDIAC CATHETERIZATION
How 3D Visualization Supports It

Klaus Drechsler, Cristina Oyarzun Laura
Department of Cognitive Computing & Medical Imaging
Fraunhofer Institute for Computer Graphics Research, Darmstadt, Germany

Georgios Sakas
Interactive Graphics Systems Group (GRIS), Darmstadt University of Technology, Germany

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Abstract: Although cardiac catheterization procedures take place under x-ray guidance, the doctor is almost blind. Vessels are almost invisible until he injects a contrast agent and looking only at 2D x-ray images and reconstructing a 3D image in his head makes it error prone and tedious. Only experienced doctors are able to accomplish this procedure with the expected results. This paper describes our preliminary work and work in progress to support doctors during cardiac catheterizations using 3D visualization.

1 INTRODUCTION

In cardiac catheterization procedures the doctor inserts a catheter into a vessel and positions it under x-ray guidance within the coronary arteries to inject a contrast agent, place a stent or a balloon to widen the vessel. The contrast agent helps him to make the coronary arteries and their potential pathologies (stenosis, calcifications) visible. Although the procedure takes place under x-ray guidance the doctor is almost blind. The vessels are almost invisible until he injects the contrast agent and looking only at 2D x-ray images and reconstructing a 3D image in real-time in his head makes it error prone and tedious. Only doctors with many years of experience are able to accomplish this procedure with the expected results. During a catheterization a doctor with less years of experience can need computer assistance before he injects the contrast agent to navigate the catheter in 3D to the destination and after he injected the contrast agent to see the arteries in 3D.

The gold standard for detecting stenosis and plaques so far is an invasive cardiac catheterization to inject a contrast agent and inspect the gathered x-ray images, called coronary angiography. We assume that in the near future the diagnostic of the vessels will be done using non-invasive computer tomography (CT) and that only the intervention, if necessary, will be done in a catheter laboratory. This assumption is not unrealistic. A steadily increasing number of hospitals are already using CT for diagnostic purposes and papers successfully investigating CT for this use case were published (e.g. (Hoffmann et al., 2005), (Mieres et al., 2007)). A combination of preoperatively gathered CT data and operatively gathered x-ray images (so called coronary angiograms) will further enhance the trust in CT for the assessment of the coronary arteries.

Our goal is to develop a sophisticated system that provides doctors preoperatively an automated quantitative analysis of the coronary arteries using CT data whose result (the found pathologies) can be directly displayed in the x-ray images gathered during the intervention. Furthermore we want to provide navigation support by displaying the position of the catheter in a 3D visualization of the heart (respectively the coronary arteries). In a second step the system could be extended to a complete training system for residents and doctors-in-training.

In this paper we present our preliminary work and work in progress to support doctors during cardiac catheterizations using a 3D heart of the patient. We use an algorithm based on raytracing in 2D space (thus on a slice by slice basis) to extract the heart from a CT image which is acquired before the catheterization procedure takes place. A tracking based vessel segmentation algorithm is used to visualize the coronary arteries and to provide an automated quan-

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titative analysis of the vessels. This allows us to show pathologies to the doctor before and during the catheterization. A further processing takes place to generate a 2D view of the 3D heart similar to a coronary angiogram which is needed for a 2D-3D registration of the two modalities. As a result our system will support the doctor during the catheterization procedure by visualizing a 3D heart that corresponds to the coronary angiogram. In addition we want to display the current catheter position in the 3D visualization by using a magnetic tracking system. This will help especially doctors with less experience to safely perform a cardiac catheterization.

The remainder of this paper is organized as follows. The next section gives an overview of related work. The following section describes our preliminary work and explains what we are currently doing. After that we conclude our paper with a critically discussion of our system.

2 RELATED WORK

In this section we give an overview of registration, heart extraction and coronary artery segmentation techniques.

2.1 Registration

When developing applications that combine and use information gathered from different modalities, registration plays an important role. The goal of the system described in (Filippatos, 2006) is to use Computer Assisted Surgery to support the implantation of a stent in the case of aortic aneurysms. They use a fiducial based registration to match the 3D CT volume to the intraoperative x-ray image. For that they adhere external markers on the chest. Then the markers are detected both in the 3D CT volume and in the 2D image using image thresholding, region growing and contour detection techniques. Finally they get the transformation matrix that matches the obtained 3D points with the corresponding 2D x-ray points and use it to initialize the 3D volume in an adequate position. For the determination of the position of the stent they need to segment the Aorta. To achieve this they use a canny edge detector. After that they obtain the centerline of the segmented aorta and use back projection of the 2D points into the 3D volume. Taking into account that the Stent will always be in the aorta they get the searched position. The work presented in (Turgeon et al., 2005) deals with similarity-based 2D-3D registration of coronary angiograms. It is worth mentioning that the comparison for the registration is made between binary images instead of gray scale images. In a first step a 4D model of the heart is obtained to create a simulation environment composed of realistic 2D and 3D images. They are using 3D computed rotational angiography comprising separate left and right coronary arteries (LCA, RCA) animated with cine-angiograms to create the simulation environment. The 3D coronary tree of the 3D volume is semi-manually segmented from one time frame of the 4D model. Once this is done the intraoperative angiograms (DRR) are generated from both the LCA and RCA 4D model. They are further processed using multiscale segmentation and then merged to get a binary image. To carry out the registration, the binary projection of the extracted coronary tree is compared with two binary angiographies by means of the entropy correlation coefficient. Finally, the downhill simplex method is used for the optimization of the translation and rotation parameters that will be applied to the 3D volume. In (Lau and Chung, 2006) the authors study how to avoid the problem of local minimas that occurs in high-dimensional image registration. They use the vessels centerline as feature for a feature based registration. For the segmentation of the vessels they use a global thresholding method to obtain a skeleton and represent it by a set of spheres with the centers set to the coordinates of the skeleton points and radii equal to their distance transform values which represents the distance to the closest boundary. After creating a DRR (Digitally Reconstructed Radiograph) of the 3D volume, the sum of squared differences is used to get the transformation matrix necessary to carry out the registration. The optimization method consist of calculating the result of the cost function in a low resolution environment, optimizing it with Powells method, and doing a final optimization with the best obtained transformation matrix in the high resolution environment.

2.2 Heart Extraction

Cardiac CT data normally contains non-cardiac structures such as ribs, lungs or the sternum. These structures obscure the view to the heart, but an isolated heart is necessary to make a visualization of the coronary arteries on the surface of the heart possible. The authors of (Lorenz et al., 2004) developed a method to extract the heart from Computed Tomography Angiography (CTA) datasets using active contours. They locate the chest and the descending aorta in all slices of the CT data in order to roughly estimate the location of the heart. Afterwards they use active contours to outline the border of the heart in a slice-by-slice manner. In (Funka-Lea et al., 2006) the authors isolate the heart from CTA scans using graph-cuts (Boykov and Jolly, 2001). First they automatically determine a seed-region within the heart by computing the volumetric barycenter weighted by intensity. In a second step they do some kind of pre-segmentation by determining the ellipsoid of maximum volume contained within the heart. The ellipsoid is used as initialization for the graph-cut algorithm. To prevent leaking into the aorta or pulmonary vessels the authors introduce a what they call 'blob'-constraint to prefer a shape whose edges are oriented perpendicular to the direction toward the center of the seed region.

2.3 Coronary Artery Segmentation

The segmentation of the coronary tree is a necessary step before an advanced quantitative analysis can take place. Several vessel segmentation algorithms have been developed in the past. A very comprehensive overview can be found in (Kirbas and Quek, 2004). It follows a description of three of the more recent work in this field. In (Hennemuth et al., 2005) the authors developed a method to segment the coronary tree in CTA datasets with one user-defined point in the middle of the aorta. Starting with this point, the authors segment and mask the aorta by using a semi-3D region growing combined with a moment-based shape analysis to fit an ellipse into the segmented region. The algorithm continues to examine connected voxel clusters around the aorta and starts a 3D region growing from those clusters which contain origins of coronary arteries. The origin of a coronary artery is detected by considering size, the center of gravity, the eccentricity and the orientation. Branches that are not automatically segmented by this algorithm can be manually added by interactively placing additional seed points. The authors of (Florin et al., 2005) propose a particle-based approach to segment the coronary arteries. They generate hypothesis (state vectors or particles) of a vessel being at a certain location, having certain orientation, referring to a certain shape with certain irregular appearance characteristics. For the latter they use a Gaussian mixture model that consists of two components to model the contrast enhanced blood and high density components like calcifications or stents. Given a starting point and a number of particles one performs random perturbations and the corresponding particles are visually and statistically evaluated. A segmentation is a weighted linear combination of the particles. In (Luengo-Oroz et al., 2007) an algorithm based on morphological grayscale reconstruction is presented to segment the coronary tree in CTA datasets. First, the user has to provide an initial point as a marker in which slice the artery is first found. Then their proposed algorithm is performed from the mark in that slice to segment the artery in it. The algorithm performs a reconstruction by dilation followed by a top-hat opening by reconstruction to extract only the bright areas of tubular-like structures. Afterwards a set of potential marks is automatically generated for the following slice. The authors use pre-knowledge from the characteristics of tubular structures to generate new marks for the next slice by searching an area of higher probability obtained from the segmentation of the previous slice. These steps are repeated for subsequent slices until there are no more potential marks.

3 GENERAL ARCHITECTURE

The general architecture of our system is shown in figure 1. All blocks were implemented at our department using VTK and ITK and recently adopted to make use of MITK (Wolf et al., 2005) which provides convenient methods to add user interaction to medical applications. The registration is currently under active development.

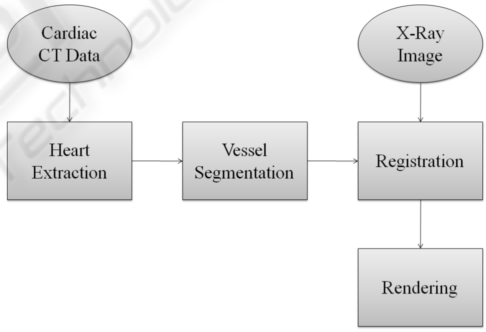

Figure 1: General architecture.

3.1 Heart Extraction

The automatic extraction of the heart from contrast agent enhanced CT data is described in (Jaehne et al., 2008). Basically a partition (labels) of the anatomical structures by automatically selecting thresholds using Otsus method (Otsu, 1979) is obtained. Then the center of gravity of the two brightest gray levels, which lies in the middle of the heart, is calculated for every axial slice. From this point a radial search ray pattern is send out in order to find the outer boundary of the heart. Overlapping structures like the aorta or the sternum prevent this method to function properly; the search rays are to long. These parts are handled in a subsequent step. On each side of the aorta and the sternum the last rays which hit on lung tissue and therefore have the correct length are automatically detected. Interpolation is then used to correct the rays between them. Afterwards the end points are connected and a binary mask is generated which is applied to the original CT data to extract the heart. The result is shown in figure 2.

Figure 2: Axial view of the extracted heart.

3.2 Coronary Artery Segmentation

The result of the heart extraction is used to segment the coronary arteries using the tracking based corkscrew algorithm, which is described in greater detail in (Wesarg and Firle, 2004). Basically it preprocesses the data by using an adaptive threshold filter that takes the gray values of three user provided seed points (start, direction and end point) and the CT data as inputs. It takes into account that the contrast agent is not equally distributed in the vessel. It follows an opening operation to remove connections to neighboring tissues and to the vessel wall behind hard plaques. The actual corkscrew algorithm gets the results of the opening operation, the original image and the output of the adaptive threshold filter to calculate a path (centerline and border) between a start and end point that lies within the vessel. Afterwards a 3D model is generated using the marching cubes algorithm (Lorensen and Cline, 1987). A three dimensional rendering of the heart with one segmented branch of the coronary artery is shown shown in figure 3.

The output of the corkscrew algorithm was successfully used to implement an automated quantitative analysis of the segmented vessel (Wesarg et al., 2006) and evaluated its result in a clinical study (Khan et al., 2006), (Wesarg et al., 2008).

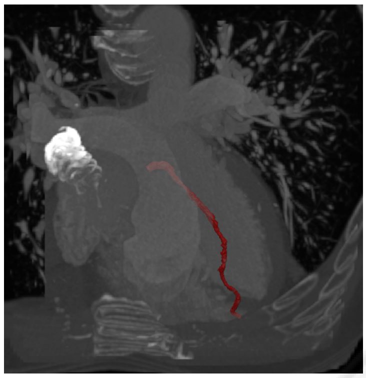

Figure 3: A maximum intensitiy projection (MIP) of the heart with one segmented branch of the coronary artery in red.

3.3 Registration

There are mainly two possibilities how a computer can assist a doctor during a cardiac catheterization, namely before and after the injection of a contrast agent. Before the contrast agent is injected, the catheters position could be located and together with the preoperatively found pathologies visualized in a 3D model of the heart. Therefore a registration of the live x-ray with the CT data based on external (e.g. fiducials) or internal (e.g. bones) markers is necessary. After the contrast agent is injected, a 3D model of the heart could be displayed (again together with the preoperatively found pathologies) such that it shows the heart from the position that x-ray generator looks at it. Therefore either a 2D-3D registration using a 2D projection of the CT data or a 3D-3D registration using a 3D reconstruction of several 2D x-ray images is necessary. Our current work concentrates on the 2D-3D registration after the contrast agent has been injected. Therefore we are currently implementing a semi-automatic registration algorithm where the doctor has to provide initially $2n$ equivalent points in the first generated 2D projection of the heart and the coronary angiogram. These points are tracked during the successive rotation of the 3D heart and generation of 2D projections to carry out an automatic point based registration of the two modalities. To track the selected points a method to project them back from 2D to 3D has to be realized. Our idea restricts the potential coronary artery segmentation algorithms to those which also provide the centerlines of the segmented vessels. We create a 2D projection of the 3D centerlines (this projection is called in the following '2DC') in addition to the normal 2D projection. If the user clicks on a vessel in the 2D projection to mark a point, it is aligned to match the underlying 2DC. This information can then be used to find the corresponding point(s) on the 3D centerline and thus in the segmented vessel. To achieve this we store with every pixel in the 2DC the coordinate(s) of its corresponding 3D voxel(s) during the projection. A problem might arise if the user selects a point in the 2D projection which represents overlapping vessels. In this case it is not clear to which 3D centerline the selected point belongs to. This situation is detected by the fact that there are more then one 3D coordinates stored together with the 2DC and used to inform the user. We could also make use of the fact that the doctor does not inject the contrast agent within both main branches at the same time and thus 'turn off' the corresponding 3D centerlines while calculating the binary projection.

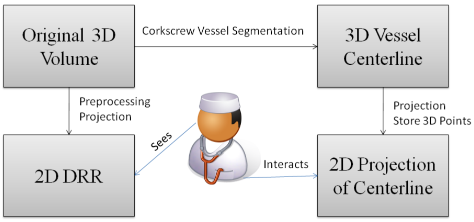

Figure 4: General architecture.

In (Langs et al., 2004) the authors describe a similar registration method. In their registration approach the user has to mark corresponding points in the 3D model and the 2D x-ray image. However, if a doctor has to select a point in 3D and a corresponding point in 2D then he has either to reconstruct a 3D image from the 2D x-ray or a 2D image from the 3D model in his head to decide which points correspond. This is what we would like to avoid and make this step as easy as possible.

3.4 DRR Generation

In (Lacalli et al., 2008) the generation of 2D projections of the heart using DRRs is described. First a preprocessing of the original CT data is necessary to avoid insufficient results due to non-cardiac structures and large cardiac cavities (e.g. ventricles and atria). The removal of non-cardiac structures has been described above. The cavities are a problem, because they are, like the coronary arteries, filled with the contrast agent and thus occlude the coronary arteries in the generated DRRs. To remove the cavities from the extracted heart a thresholding operation on the labeled CT data (that was generated in the heart extraction step) is first applied to remove everything but the highest label that correlates with both the cavities and the arteries. Afterwards the coronary arteries are removed by applying an erosion operation followed by a neighborhood filter along all the three orthogonal axes. Finally a dilation operation is applied to restore the original size of the cavities. The result is used as a mask to remove the cavities from the extracted heart. A perspective projection is then carried out to generate the DRR to simulate a coronary angiogram. The result is shown in fig 5.

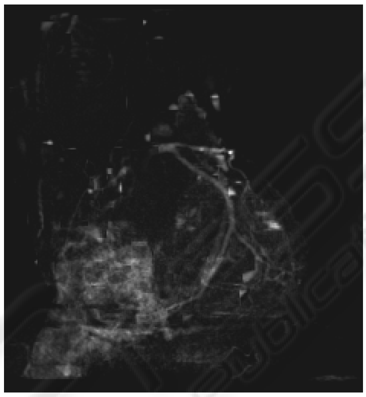

Figure 5: Digital Reconstructed Radiography of the heart. The vessels are clearly visible.

4 CONCLUSIONS AND DISCUSSION

This paper presented our preliminary work and work in progress to support cardiac catheterizations through 3D visualization. We described the building blocks of our proposed system and explained their function. Though the heart extraction algorithm provides good results, it has some flaws which can be traced back to the way it works. It only uses axial slices to process the volume. While the heart is fairly well extracted in the axial orientation, it still needs some improvements for the other orientations. 6 shows the coronal view of the extracted heart. At the bottom it can clearly be seen, that structures are shown that do not belong to the heart.

Currently we are investigating an approach based on deformable models to extract the heart from a CT volume. Initial results are promising and are subject for further publication. The corkscrew algorithm already proved its usefulness and robustness in a clinical setup. However, currently it is only able to segment one branch of a vessel tree. It is not able to detect bifurcations and automatically follow them in order to segment the complete coronary tree. The setting of three seed points is sufficient to segment one branch of the tree, but very tedious and time-consuming if done for the whole tree. Recently we started to investigate the possibilities to enhance the corkscrew algorithm to automatically detect bifurca-

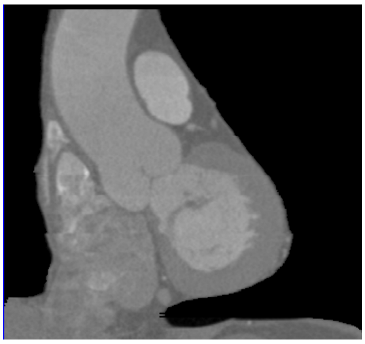

Figure 6: Coronal view of the extracted heart.

tions. Furthermore our goal is to minimize user interaction. Ideally the user only has to provide one start point to segment the whole coronary tree. Direction and end point should be automatically detected by taking anatomical knowledge of the heart into account. Another problem we found with the current implementation of the corkscrew algorithm is that the results slightly differ when the seed points are not set at exactly the same coordinates. The reason for this behavior has to be further investigated, but an automated seed point correction should take place to ensure reproducible results. An approach to align the specified seed points towards the vessel center is described in (Egger et al., 2007). Rays are sent out radially from the seed point with a user defined length. From the intersections with the vessel walls the direction to align the seed points can be computed.

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