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Determination of the Absolute Axial Orientation of Intracoronary Ultrasound Images in Fusion with Biplane Angiography

A Wahle,[1] G P M Prause,[1,3] S C DeJong,[2] M Sonka[1]

The University of Iowa, [1]Electrical and Computer Engineering, [2]Internal Medicine, Iowa City, Iowa, USA; [3]MeVis Institute at the University of Bremen, Bremen, Germany

Abstract

While intravascular ultrasound (IVUS) gains increasing importance, assessment of spatial structures still lacks a geometrically correct 3-D reconstruction. The IVUS frames are usually stacked up to form a straight vessel, neither considering any curvature nor the axial twisting of the catheter during the pullback. Quantification of this simplified data inevitably results in significantly distorted values.

To solve this problem, our approach assigns the results from IVUS segmentation to their geometrically correct spatial locations and orientations. One of the major tasks in this reconstruction is the determination of the axial rotation of the IVUS frames. This paper presents a new method to derive the absolute orientation of an IVUS frame set from the out-of-center location of the imaging catheter without any additional user interaction.

1. Introduction

The fusion of the two commonly used modalities for the assessment of coronary artery disease, angiography and intravascular ultrasound, promises to combine their advantages and to overcome their well-known problems. While biplane angiography delivers accurate information about the vessel topology and shape, the cross-sectional data are restricted to simple shapes like ellipses, and no information is provided concerning plaque or wall thickness. These parameters have to be derived indirectly from the lumen [1]. In contrast, IVUS allows a high resolution assessment of plaque and vessel walls [2], but does not facilitate the determination of location and especially orientation of a specific IVUS frame in the 3-D space. Conventional IVUS reconstruction systems are restricted to a straight stacking of the IVUS pullback sequence, completely neglecting the vessel curvature. Since the two modalities are complementary, a combination of both opens a way to obtain accurate geometric as well as cross-sectional data.

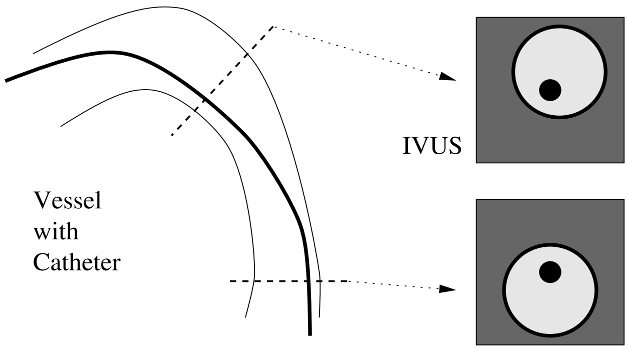

Figure 1: Scheme of the optimization of the absolute orientation; the bended catheter can be identified in both angiograms and IVUS images.

The major problem is to match an IVUS image with a concrete 3-D location and a spatial orientation. The localization problem may be solved by constant angiographic supervision of the catheter during the pullback along with 3-D reconstruction of the location of its tip. For example, Evans *et al.* [3] and Shekhar *et al.* [4] proposed systems based on this strategy. Because a constant X-ray exposure over several minutes is usually neither acceptable for the patient or the personnel, nor for the X-ray system, the catheter path may be imaged once at pullback start and the images are distributed uniformly along the path instead [5, 6].

The orientation of the IVUS frame is a comparably complex problem. An independently performed local frame-by-frame determination by backprojection of the IVUS cross-sections into the angiographic images as proposed by Shekhar is vulnerable to small errors or ambiguities in the profiles. As a solution for the *relative* twist between adjacent IVUS frames, Laban *et al.* [5] derived the catheter torsion analytically from the Frenet-Serret rules. Recently, we presented a discrete version of the Frenet-Serret rules for estimating the orientation changes between adjacent IVUS frames [6]. However, the question remains what the *absolute* axial orientation of the resulting frame set is. The problem is comparable to fitting a sock on a leg [5]: While

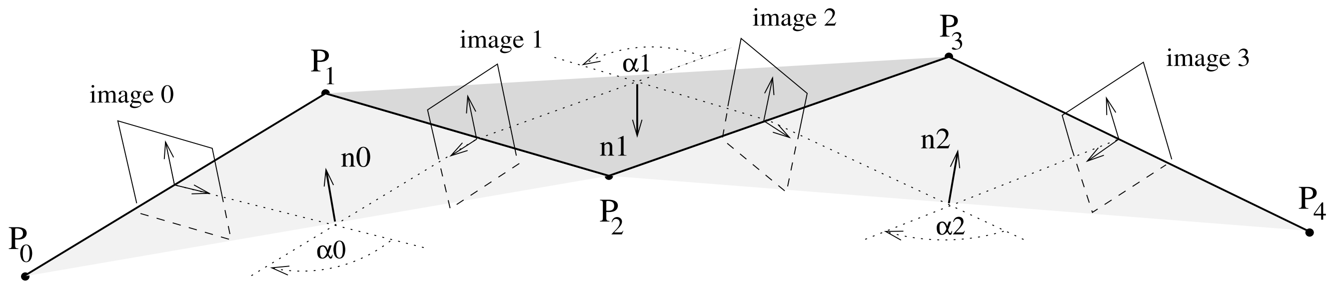

Figure 2: Sequential triangulation algorithm for calculation of catheter twist.

the leg (catheter path) is stable, the sock (axial catheter orientation) can freely be rotated around the leg. In the current systems, this problem is usually solved by manual interaction.

We are using the bending behavior of the imaging catheter as a reference, which is expected to fall in the location of minimum energy within the vessel. The catheter usually does not follow the center line of the vessel, and is forced to an out-of-center location due to bending (Fig. 1). This out-of-center location is identified in both angiograms and in all IVUS images, and used as an artificial landmark for the determination of the absolute orientation.

2. Methods

2.1 3-D Trajectory from Angiography

The entire process starts with the extraction of the catheter path and the inner lumen of the vessel from the angiograms. The catheter path is extracted using a dynamic programming approach, which is optimized to find the local peaks in the vessel profile. The catheter path is then used as a guide line for the detection of the vessel borders according to [7]. This is done in both angiograms.

From the known imaging geometry, the 3-D coordinates of the path can be reconstructed from its two corresponding projections. For this purpose, the well established and evaluated system developed at the German Heart Institute of Berlin is utilized [1, 8].

2.2 Relative Orientation

The relative changes in the orientation of adjacent IVUS images are analytically determined using a discrete version of the Frenet-Serret rules. This system has been presented in detail in [6].

Using the three points of the catheter path next to the two adjacent frames, a circumscribing circle is calculated. The sector between the two images is considered a part of the circle. Thus, the new frame is calculated by rotating the previous frame around the normal n_i of the circle by the enclosed angle α_i (Fig. 2).

2.3 Absolute Orientation

After the relative orientations have been determined, all frames are preliminary mapped into 3-D using an initial absolute orientation. Aim of the following procedure is to obtain a correction angle, by which all IVUS frames have to be rotated around their local normal axes, to minimize the reconstruction error. Therefore, the out-of-center location of the catheter can be utilized, which occurs due to bending and can be assumed stable if a sheathed catheter is used during the pullback.

2.3.1 IVUS Segmentation

For comparison with the angiographically reconstructed inner lumen, the lumen contours have to be segmented from the IVUS images. Again, we are using a well established and validated algorithm presented previously in [2]. For the purpose of establishing the absolute orientation of the frames, only the contour of the inner lumen is evaluated. Of course, the other contours, indicating the internal and external laminae, can be acquired in the same step and used later for quantifications.

2.3.2 Mapping of IVUS Contours

The segmented contours of the inner lumen are mapped into the 3-D IVUS frames by calculating the 3-D locations of each contour point. Since the absolute orientation of the frames is not yet known, an initial orientation is used that is normalized for the first frame, while the orientations of the subsequent frames are determined from the catheter twist as described in section 2.2.

The frames are expected to be oriented perpendicular to the catheter path, thus the IVUS pixels are mapped on a plane orthogonal to the local direction of the trajectory. The center of an IVUS image (i.e. the catheter itself) is pierced by the catheter path. The locations of the frames along the catheter path are determined from their timestamps, assuming a constant pullback speed. Each contour point can be associated with a pixel, thus its 3-D location is known after this mapping.

2.3.3 Out-of-Center Location

The determination and evaluation of the catheter's out-of-center location are the core algorithms of our new approach. The inner lumen is usually of circular or elliptic shape, except at stenosed locations. As a result of the 3-D reconstruction from the angiograms, an elliptical cross-section can be generated. The center point of this ellipse is the origin of the out-of-center vector, while the reconstructed 3-D location of the respective catheter element is the end point of the vector. These vectors are created for all locations for which a segmented IVUS image exist.

From the IVUS contours of the inner lumen, their points of weight are calculated by

$$S_j = [\overline{u}_j, \overline{v}_j] = \frac{1}{n_j} \sum_{i=0}^{n_j-1} [u_{ij}, v_{ij}] \tag{1}$$

for contour j containing n_j points $[u_{ij}, v_{ij}]$. The 2-D out-of-center vector can easily be derived, originating from S_j to the catheter location in the center of the image, and then mapped into 3-D as described before.

2.3.4 Optimization Process

For each IVUS frame, two parameters exist: The first value indicates the difference angle between the angiographic and the IVUS out-of-center vectors; the second value indicates the length of the out-of-center vector, and thus the strength of the effect. The correction process is a statistically based optimization that incorporates several weighting mechanisms.

Due to local tolerances, either from the reconstruction process, slight mismatches in IVUS localization, resolution, etc., the weighting does not only include the effect strength, but also the reliability of the local data. This is performed by analyzing the data within a moving window of fixed size along the catheter path (Fig. 3). Within the window, each difference angle is weighted by the vector length. Due to the higher resolution, the mapped out-of-center vectors from the IVUS images are used for the weight. For each window k, the weighted mean $\overline{\varphi}_k$ and the weighted standard deviation $\sigma(\varphi_k)$ of the difference angle as well as the sum of weights $\Sigma\mu_k$ are calculated.

In the next step, the correction angle is calculated from the values over all windows. Part of the moving window concept is that adjacent windows differ only by one element, thus introducing smooth changes from window to window. The positive weight is the value of $\Sigma\mu_k$, while the negative weight results from the local tolerances $\sigma(\varphi_k)$. The correction angle results from the weighted mean

$$\overline{\varphi}_{\text{corr}} = \sum_k \left(\overline{\varphi}_k \frac{\Sigma\mu_k}{\sigma(\varphi_k)} \right) \Bigg/ \sum_k \left(\frac{\Sigma\mu_k}{\sigma(\varphi_k)} \right) \tag{2}$$

and is to be applied to all IVUS frames.

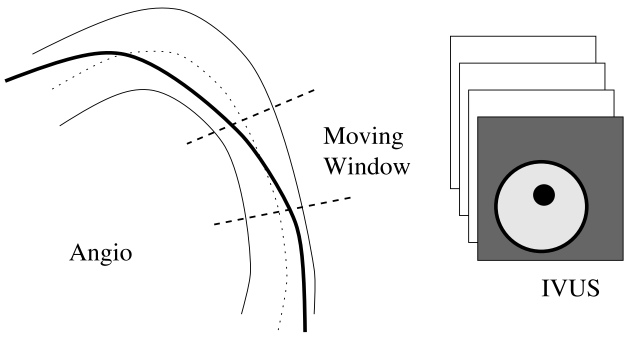

Figure 3: Center line as reference in angiograms, calculation of local correction angles in fixed-sized moving windows.

3. Results and Discussion

The algorithm is currently in the validation phase, thus only preliminary results can be presented. Up to now, the method was tested in one cadaveric pig heart that was immersed in a water bath and filled with diluted contrast dye for angiography. Three manual IVUS pullbacks were performed using a mechanically driven 2.9F, 30MHz imaging catheter. A detail along the distal part of the right coronary artery can be seen in Fig. 4. The algorithm could identify the relevant areas reliably, e.g. the arcs where the catheter hits the inner side of the vessel, as well as the straight part where the catheter hits the outer side of the vessel.

However, due to inhomogeneous pullback speed, slight localization errors occured. While small deviations are detected from high local tolerances, resulting in a strongly reduced weight, longer segments may falsely seem to be reliable. In the given example, these errors in the distal part of the artery resulted in an axial mismatch of 33.6° compared to the proximal part, which was considered to be accurate by visual comparison. After discarding the distorted area (15 connected IVUS frames out of 107 of the entire sequence with 1mm steps), the difference was reduced to 9.4°.

Reasons for the remaining errors may be found in the mechanical setup of the catheter as well as the manual pullback, which include phase shifts during the rotation of the transducer [9]. It is remarkable that 69.2% of the weights were distributed over the proximal half of the vessel (before manual intervention), which indicates that the algorithm focused on the more stable proximal part as intended. However, the tolerances from the manual pullback and especially from the phase shifts in the mechanically driven catheter system could only partially be considered. Using automated pullback devices and further progress in catheter technology should limit these effects to an acceptable amount. The need of manual verification for distorted areas could then be avoided.

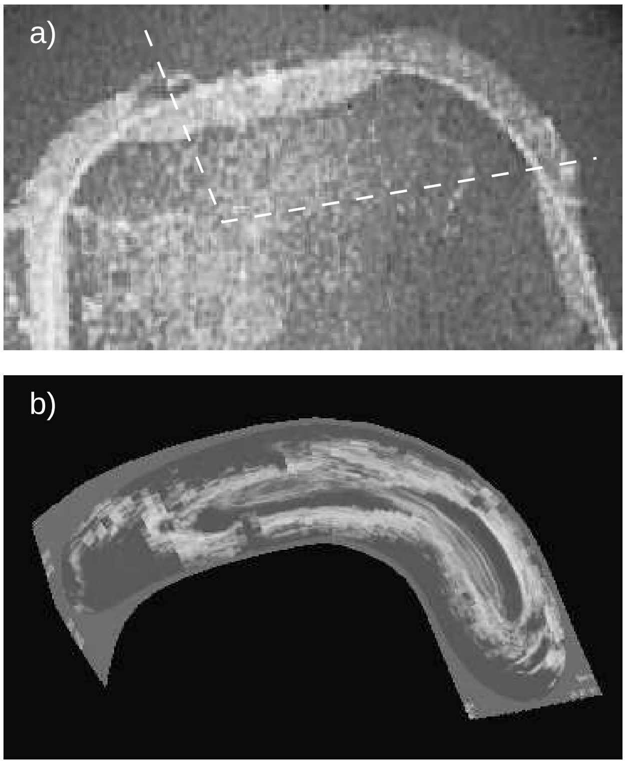

Figure 4: a) Detail of an angiogram in a cadaveric pig heart; b) cut through a voxel cube resulting from geometrically correct assignment of the IVUS pixel data, with uncorrected ring-down halo to visualize the catheter.

4. Conclusions

Although the current study is still preliminary, the presented method promises to solve a major problem in the determination of the absolute orientation of the IVUS frames during reconstruction. The combination of an analytical calculation of the relative changes between adjacent images and the absolute axial orientation on the basis of the bending behavior of the imaging catheter showed good results even in the presence of errors introduced by the acquisition process. The systematic nature of these distortions provides a good potential for either the successful development of an automated correction procedure or methods to eliminate the effects. The developed system is able to deliver a high quality reconstruction of the IVUS data, and thus substantially improves the clinical applicability.

Acknowledgments

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Address for correspondence: Andreas Wahle, PhD, The University of Iowa, Electrical and Computer Engineering, 4400 EB, Iowa City, IA 52242–1595, U.S.A.; Fax: ++1 (319) 335–6028, E-mail: <a.wahle@computer.org>