Accurate 3-D Fusion of Angiographic and Intravascular Ultrasound Data

Andreas Wahle,[1] Guido P. M. Prause,[1*] Steven C. DeJong,[2] and Milan Sonka[1]

The University of Iowa, Departments of [1]Electrical and Computer Engineering, and [2]Internal Medicine — Iowa City, IA 52242, U.S.A.

[*]Author is now with the MeVis Institute, University of Bremen — D-28359 Bremen, Germany

Abstract

Biplane coronary angiography and intravascular ultrasound are complementary methods to assess coronary artery disease. The first one delivers accurate information about the vessel topology and shape, but only restricted data concerning the vessel cross-section. The latter one provides detailed information about the shape and composition of vessel wall and plaque, but fails to consider the geometrical relationships between adjacent images. Thus, a combination of both methods enables judgement of both the longitudinal and cross-sectional geometry of the coronary arteries. In this paper, we present an accurate method for fusion of biplane angiography and intracoronary ultrasound.

1 Introduction

For decades, selective coronary contrast angiography has been the definite catheter-based imaging technique for the diagnosis of coronary artery disease. Apart from several well-established systems for quantitative analysis of individual coronary stenoses (QCA), methods for reconstruction of the spatial morphology of vessels from biplane projections have been developed [1, 2]. However, the major limitation of X-ray angiography is its restriction to the assessment of the inner lumen. For example, the wall thickness and the composition of the plaque cannot be determined. Recently, intravascular ultrasound of the coronary arteries (IVUS) evolved as a complementary method in cardiovascular diagnosis. Using a catheter with an ultrasonic transducer in its tip, pulled back during imaging, the luminal cross-sections can be determined as well as the wall thickness, and even the composition and orientation of the plaque [3, 4]. A major drawback of IVUS is its in-ability to reconstruct the vessel segment geometrically correct, i.e. considering the vessel curvature when assigning the detected plaque to specific locations.

Up to now, 3-D reconstruction of vessels assessed by IVUS has been performed by simply stacking the images up to a rectangular – but straight – volume. These methods cannot reflect the real curvature of the vessel, which has to be considered since vessels are completely straight only in a minority of cases. Although most algorithms have proven high accuracy in phantom studies using straight objects, they usually fail as soon as the vessel curvature gets strong enough [5].

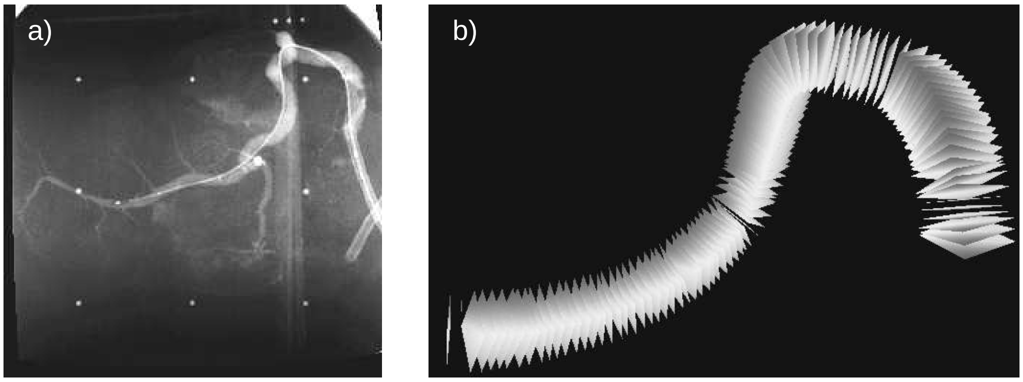

Figure 1: Example for correct orientation of IVUS images: a) lateral projection of a biplane image of an extracted cadaveric pig heart in a water bath with the catheter; b) spatial reconstruction of the IVUS images as VRML model (pixel data omitted).

In particular, there are two effects that have to be handled sufficiently [6, 7, 8]:

- Due to vessel *curvature*, the IVUS slices are no longer in parallel. This distorts any volumetric analysis, because volume fragments at the inner side of the vessel related to its curvature will be overestimated and fragments on the outer side underestimated.
- Due to vessel *torsion*, the axial orientation of an ideal IVUS catheter within the vessel is no longer constant. The torsion is zero only if the vessel lies within a plane. Whenever the vessel moves outside this plane, the catheter twists axially, and this rotation must be considered in the 3-D reconstruction as well.

Our solution for these problems is to employ spatial fusion of the coronary angiography and the intravascular ultrasound data. The 3-D vessel shape and topology are determined by accurate reconstruction from biplane angiograms of known imaging geometry. The vessel cross-sections are extracted from IVUS data acquired in the same session as the angiographic images. For both tasks, our previously developed and validated systems are utilized. The aim of our new approach is the exact assignment of the cross-sectional data to the vessel segment in both location and orientation (Fig. 1).

2 Image Fusion

2.1 3-D Reconstruction of the Pullback Path

The catheter path during pullback is extracted from the dewarped biplane angiograms, beginning with interactive marking of the tip and a small number of proximal guide points, at least up to the end of the pullback. Then, the catheter is extracted automatically along these points by a dynamic programming approach, and an accurate 3-D model of the catheter within the respective vessel segment is automatically generated. It is assumed that the catheter tip with the transducer keeps in its initial path, which is approximately true here since sheathed catheters are used. Each single point of the catheter can be reconstructed by calculating its projection rays in 3-D from the known imaging geometry, using the epipolar constraint. Theoretically, these rays should intersect in the original 3-D location at imaging time, provided the assumed imaging geometry is correct and both projection points have been identified accurately. Since this is hard to ensure, an approximation has to be performed to find the location of the point to reconstruct. Furthermore, the resulting ray bundles have to be matched, i.e. those pairs of elements have to be found that correspond in both 2-D projections.

The reconstruction algorithm as initially reported in [9] has meanwhile been replaced by the comprehensive approach as developed at the German Heart Institute of Berlin [1, 2] to achieve higher accuracy. The imaging geometry neither needs to be orthogonal, nor is a stable iso-center required, and is refined from a set of given parameters using some reference points in the angiograms. For an absolute measure, a calibration ball with two markers is used, although any other object of known size visible in both projections can be utilized. Minor changes were applied to stabilize the cost matrix approach for correspondence finding on larger vessel segments, mainly to obtain a smooth pullback path that is not distorted by local roughness.

2.2 Mapping of the IVUS Images

After reconstructing the 3-D trajectory, each IVUS image has to be assigned to a specific location along the pullback path. A constant supervision of the catheter tip movement by angiography as proposed by Evans *et al.* [7] is not acceptable in clinical application, due to physical limitations of the imaging device and the additional X-ray exposure of the patient. Thus, in the worst case only one biplane image pair is available, namely at the time of pullback start. On the other hand, it may be assumed that the speed of the pullback is constant, which is approximately true if a mechanical pullback device is used [6]. Since the length from pullback start to any location on the path can be determined accurately [1, 2], each IVUS image can be localized from its timestamp.

2.3 Calculation of the Catheter Twist

When the images are assigned to their locations, for each IVUS image its spatial orientation has to be determined. For this purpose, a sequential triangulation method is used to calculate the relative twist between adjacent IVUS images (Fig. 2): For time instances i and $i+1$, both images are located halfway between three consecutive points P_i, P_{i+1}, P_{i+2} at $S_i = (P_i + P_{i+1})/2$ and $S_{i+1} = (P_{i+1} + P_{i+2})/2$; the images are perpendicular to the tangent vectors $t_i = P_{i+1} - P_i$ and $t_{i+1} = P_{i+2} - P_{i+1}$; the center of the circumscribed circle of the triangle defined by $T_i = (P_i, P_{i+1}, P_{i+2})$ is determined as the intersection of the perpendicular bisectors of the tangent vectors t_i and t_{i+1}; the orientation of image $i+1$ is determined by rotating image i by α_i around the normal vector $n_i = t_i \times t_{i+1}$ of the triangle T_i; finally, the center of image $i+1$ is shifted to tangent vector t_{i+1} since the perpendicular bisectors are generally not equal in length. In the special case that the vessel is straight, thus (P_i, P_{i+1}, P_{i+2}) are collinear, no circle can be defined and the orientation remains unchanged.

This inductive scheme is an approximation to the Frenet-Serret frame, which cannot directly be used in this case since there exists only a set of discrete points (a direct application of the Frenet frame by modelling the pullback path as a function for which a third derivative

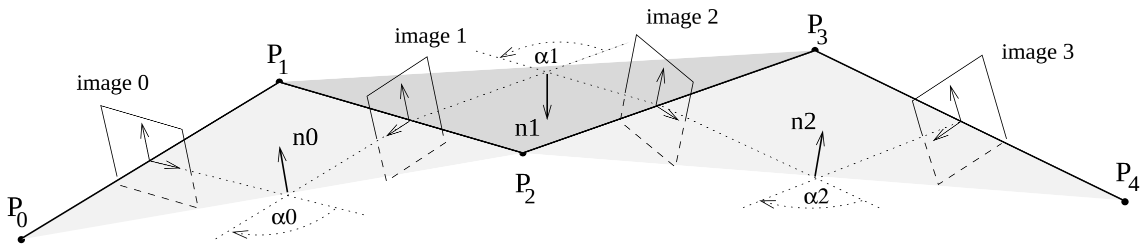

Figure 2: Calculation of the relative twist by sequential triangulation.

exists was performed by Laban *et al.* [6]). Although the relative twist can be calculated, the inductive anchor is still missing and thus the absolute orientation ambiguous. One way to achieve correct overall match of the IVUS and angiography data is to use anatomical landmarks, e.g. branching vessels. Unfortunately, the locations and orientations of branches frequently cannot be determined accurately enough both in angiographic and in IVUS images [9]. Algorithms to solve this problem automatically by using further information and physical constraints are under development. Currently, the absolute orientation is determined by user interaction.

To obtain a scalar measure for the torsion, i.e. how much did the current IVUS image axially twist compared to pullback start, a reference plane is used. This plane is calculated by bilinear regression from the points of the reconstructed 3-D pullback trajectory. Afterwards, the pullback path is projected onto this plane, thus creating a torsion-free copy of the original path. The local twist can now be calculated for each IVUS image by the difference angle between the viewup vectors for both torsion-free and the torsion-loaded versions.

2.4 Processing of the IVUS Images

Separately from the angiograms, the IVUS images are segmented, resulting in a set of contours [3]. In contrast to other approaches, our system extracts the contours for the coronary lumen, the plaque, including its hard and soft components, as well as both internal and external elastic lamina borders. This is done in a semi-automated process for the entire image sequence. An elliptical region of interest (ROI) has to be marked only in the first image, which is then adapted from image to image. However, the user may interrupt the automated process to adjust the ROI at any stage.

After segmentation and mapping of the contours into 3-D space, a surface model of the inner and outer borders of the vessel wall, as well as the plaque, can be generated. This model is represented together with the spatially correct locations of the angiograms and the X-ray sources in a VRML-2.0 world, thus allowing visualizations by any appropriate browser regardless of the platform used.

3 Results and Discussion

We tested our algorithms in several studies, using phantoms and cadaveric hearts for assessment of the accuracy and reproducibility of the methods. While the validation of our system is still

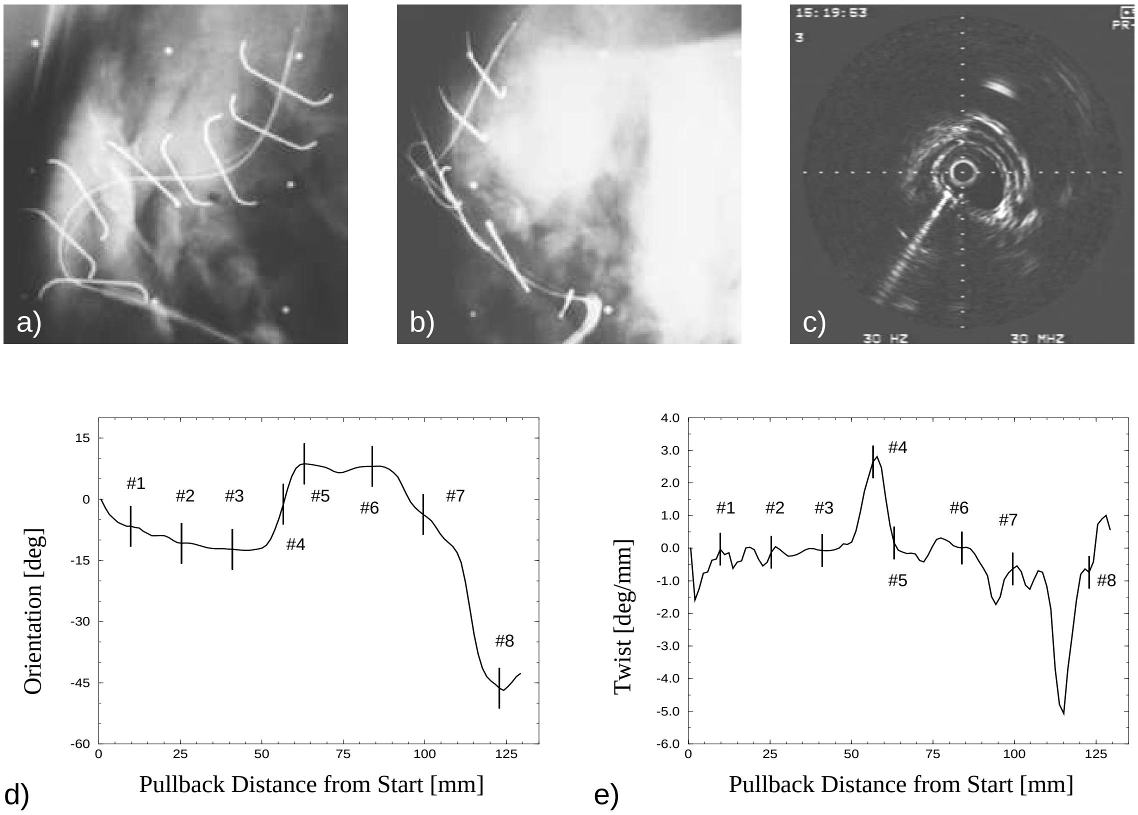

Figure 3: Cadaveric pig heart with metal clips: a) frontal and b) lateral angiographic projections, catheter tip at the distal endpoint (top of images) before pullback starts; c) IVUS image with peak caused by a clip; d) orientation relative to pullback start, clips locations are marked with numbers counted from distal to proximal; e) first derivative of d), i.e. relative twist between adjacent locations.

in progress, analyses in helical phantoms have already shown a good match of the measured and the analytically determined twist [8]. For the in-vitro studies in pig hearts, a typical pullback length was 100–120 mm, with a manual pullback speed of 0.9–1.3 mm/s. The overall twisting range along individual pullbacks was 41.8° in the least tortuous up to 118.1° in the most tortuous vessel. These results show the high significance of the axial twist.

To establish the accuracy in real vessels, pig hearts were supplied with metal markers. As a preliminary result, a pullback sequence of a right coronary artery has been exemplarily evaluated (Fig. 3). Seven of the eight markers (except #8) could be imaged during the pullback, for which a constant speed of 1.3 mm/s was assumed. Using only one angiographic image at pullback start (transducer located 9.8 mm distal to the first clip) as reference, the signed matching error in mean and standard deviation was 0.22 ± 3.56 mm. After re-adjusting the pullback speed by alignment with the first (#1) and last (#7) clips, the matching improved to 1.59 ± 1.65 mm. The estimated real speed of the manual pullback was 1.35 ± 0.30 mm/s. This high standard deviation indicates that the use of an automated pullback device is strongly recommended.

The orientation error was calculated from the difference of the peak vectors visible in the 3-D mapped IVUS images vs. the clips locations as reconstructed from the angiograms. The overall orientation was automatically adjusted to minimize the mean difference angle, the standard deviation of the remaining error angles was 14.4°. The highest deviation from the mean error could be measured on clips #4 and #7, thus in areas of high twisting. Slight mismatches in the clips' locations are especially significant here, since they distort the estimation of the orientation. Possible additional sources for the tolerances are again the manual pullback, which introduces unsystematic twists by the hand of the operator, and torsions within the catheter system that are currently not considered by our method. Further evaluation is in progress.

In conclusion, our system provides high accuracy in 3-D reconstruction of the vessel topology, and a spatially correct assignment of plaque and wall data as delivered by the IVUS segmentation. Thus, high accuracy volumetric quantifications are feasible, as well as geometrically accurate and realistic visualizations of the vessel.

Acknowledgments

This work has been supported in part by grants Pr 507/1-2 and Wa 1280/1-1 of the *Deutsche Forschungsgemeinschaft*, Germany, and by grants IA-94-GS-65 and IA-96-GS-42 of the *American Heart Association*, Iowa Affiliate.

References

[1] A. Wahle, E. Wellnhofer, I. Mugaragu, H. U. Sauer, H. Oswald, and E. Fleck, "Assessment of Diffuse Coronary Artery Disease by Quantitative Analysis of Coronary Morphology based upon 3-D Reconstruction from Biplane Angiograms", *IEEE Transactions on Medical Imaging*, vol. 14, no. 2, pp. 230–241, June 1995.

[2] A. Wahle, *Präzise dreidimensionale Rekonstruktion von Gefäßsystemen aus biplanen angiographischen Projektionen und deren klinische Anwendung*, no. 152 in Fortschritt-Berichte, Reihe Biotechnik (17), VDI Verlag, Düsseldorf, 1997. (in German).

[3] M. Sonka, X. Zhang, M. Siebes, M. S. Bissing, S. C. DeJong, S. M. Collins, and C. R. McKay, "Segmentation of Intravascular Ultrasound Images: A Knowledge-Based Approach", *IEEE Transactions on Medical Imaging*, vol. 14, no. 4, pp. 719–732, Dec. 1995.

[4] J. Dijkstra, A. Wahle, G. Koning, J. H. C. Reiber, and M. Sonka, "Quantitative Coronary Ultrasound: State of the Art", in *Cardiovascular Imaging II*, J. H. C. Reiber and E. E. van der Wall (eds), Kluwer, Dordrecht, June 1998. (in press). [*]

[5] S. P. Wiet, M. J. Vonesh, M. J. Waligora, B. J. Kane, and D. D. McPherson, "The Effect of Vascular Curvature on Three-Dimensional Reconstruction of Intravascular Ultrasound Images", *Annals of Biomedical Engineering*, vol. 24, no. 6, pp. 695–701, Nov./Dec. 1996.

[6] M. Laban, J. A. Oomen, C. J. Slager, J. J. Wentzel, R. Krams, J. C. H. Schuurbiers, A. den Boer, C. von Birgelen, P. W. Serruys, and P. J. de Feyter, "ANGUS: A New Approach to Three-Dimensional Reconstruction of Coronary Vessels by Combined Use of Angiography and Intravascular Ultrasound", in *Proc. Computers in Cardiology 1995, Vienna AT*, pp. 325–328, IEEE press, Piscataway NJ, 1995.

[7] J. L. Evans, K. H. Ng, S. G. Wiet, M. J. Vonesh, W. B. Burns, M. G. Radvany, B. J. Kane, C. J. Davidson, S. I. Roth, B. L. Kramer, S. N. Meyers, and D. D. McPherson, "Accurate Three-Dimensional Reconstruction of Intravascular Ultrasound Data; Spatially Correct Three-Dimensional Reconstructions", *Circulation*, vol. 93, no. 3, pp. 567–576, Feb. 1996.

[8] G. P. M. Prause, S. C. DeJong, C. R. McKay, and M. Sonka, "Towards a Geometrically Correct 3-D Reconstruction of Tortuous Coronary Arteries Based on Biplane Angiography and Intravascular Ultrasound", *International Journal of Cardiac Imaging*, vol. 13, pp. 451–462, 1997.

[9] G. P. M. Prause, S. C. DeJong, C. R. McKay, and M. Sonka, "Semi-Automated Segmentation and 3-D Reconstruction of Coronary Trees: Biplane Angiography and Intravascular Ultrasound Data Fusion", in *Proc. Medical Imaging 1996: Physiology and Function from Multidimensional Images, Newport Beach CA*, vol. 2709, pp. 82–92, SPIE, Bellingham WA, 1996.

[*] **The correct reference [4] is:**
J. Dijkstra, A. Wahle, G. Koning, J. H. C. Reiber, and M. Sonka, "Quantitative Coronary Ultrasound: State of the Art", in *What's New in Cardiovascular Imaging?*, J. H. C. Reiber and E. E. van der Wall (eds), vol. 204 of *Developments in Cardiovascular Medicine*, pp. 79–94, Kluwer, Dordrecht, 1998.