3-D Fusion of Biplane Angiography and Intravascular Ultrasound for Accurate Visualization and Volumetry

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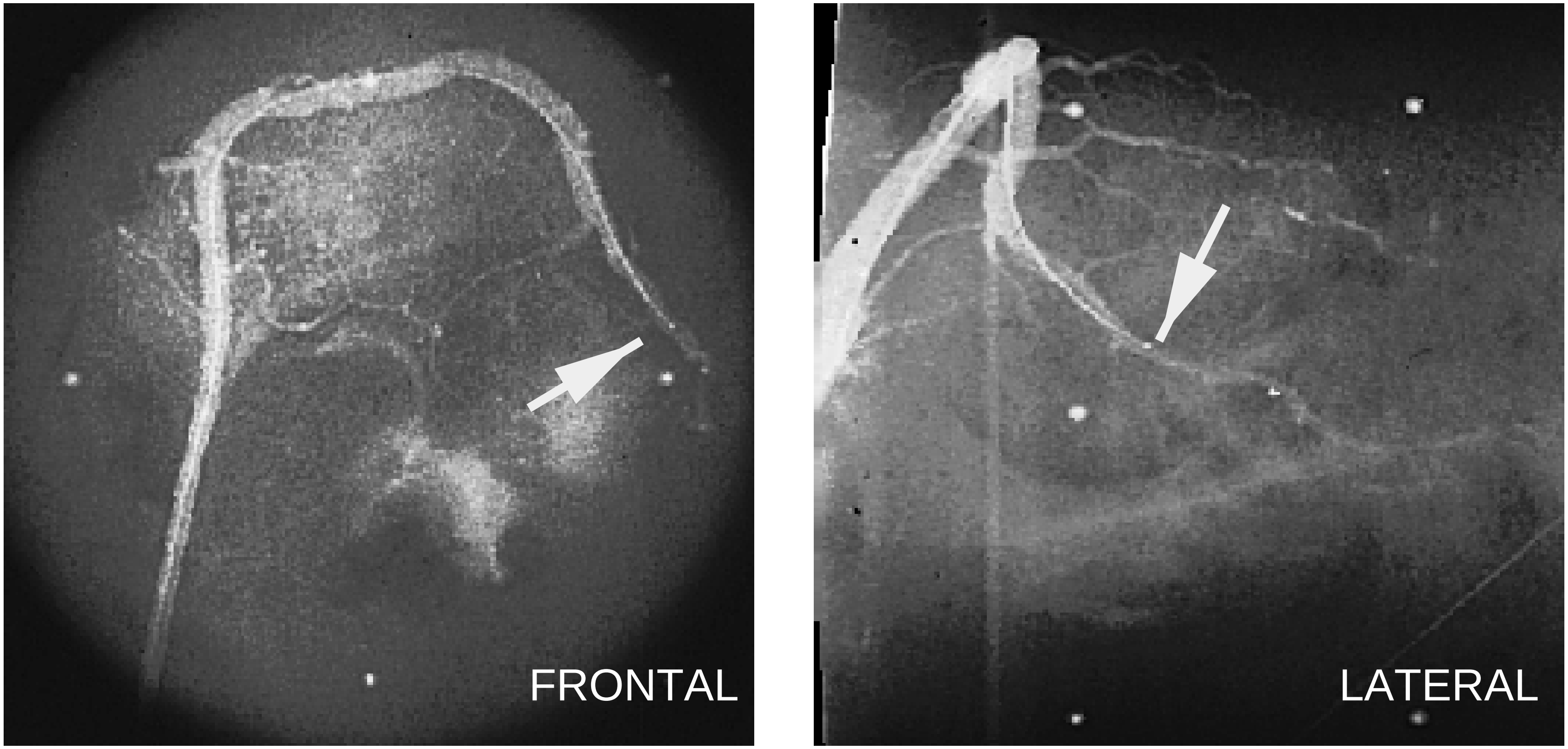

Figure 1: Preprocessed biplane angiograms in a right coronary artery of an extracted cadaveric pig heart with inserted IVUS catheter; the arrows mark the location of the IVUS transducer at pullback start, i.e. at the most distal location.

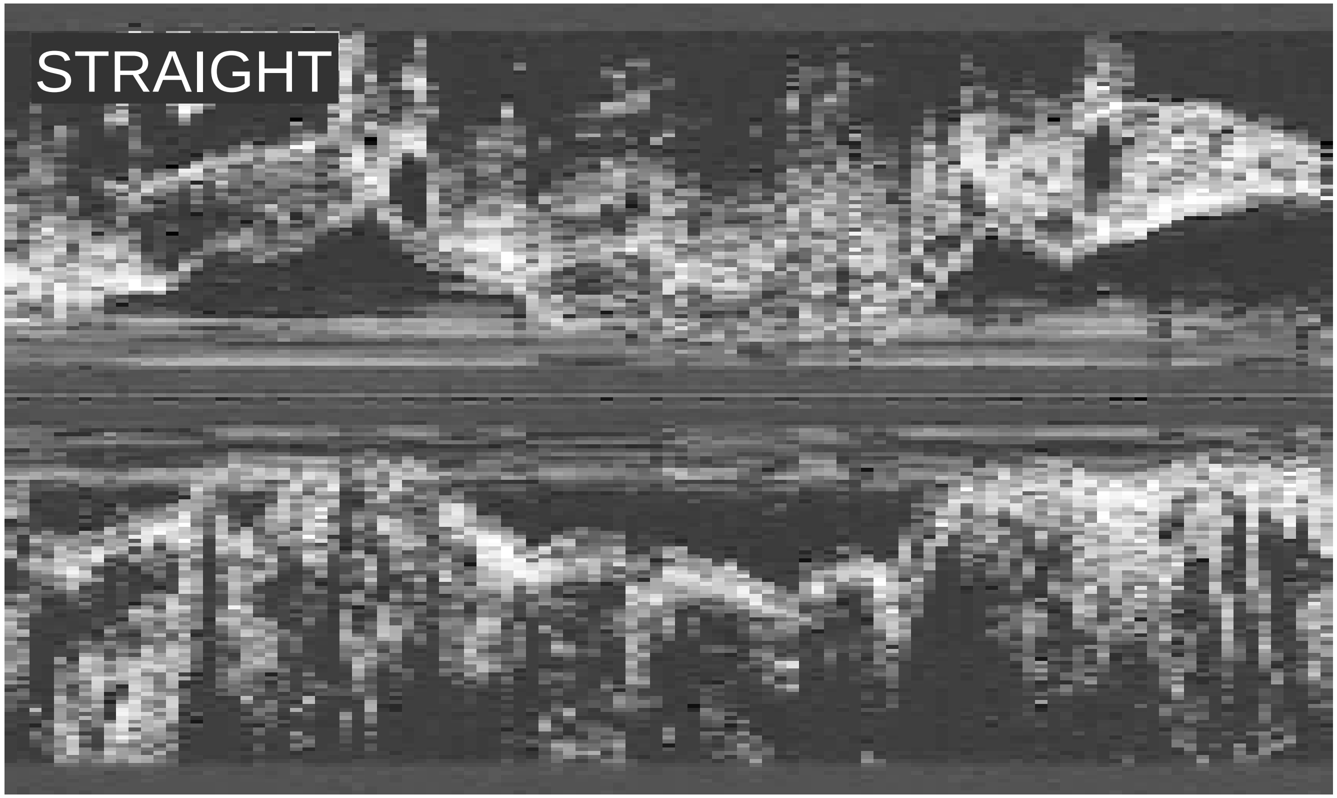

Figure 2: *Conventional 3-D IVUS Reconstruction* — simple straight stacking of the images, figure shows a longitudinal slice through the stacked volume; note that the catheter is straight while the vessel does not follow the real path.

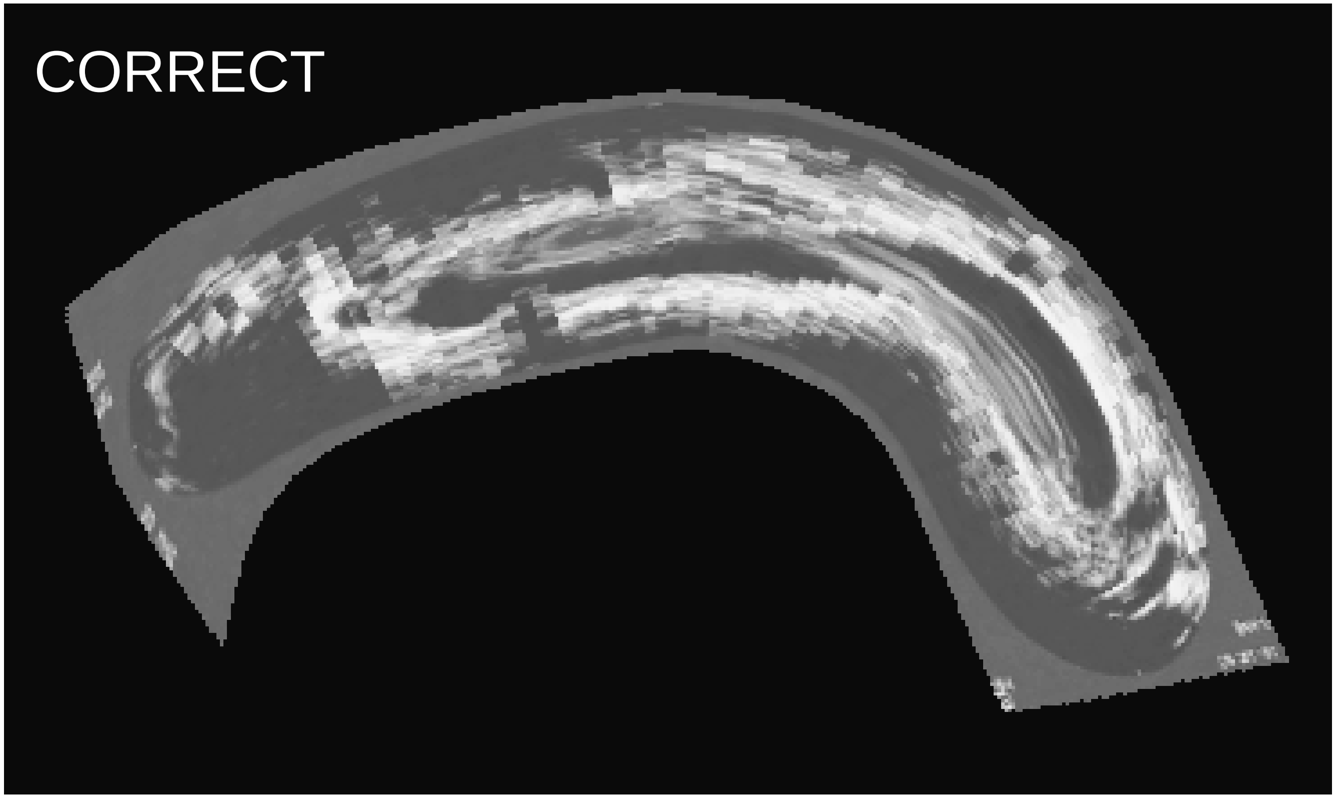

Figure 3: *Geometrically Correct Reconstruction* — slice through the voxel cube generated with our algorithm, considering the real 3-D catheter path and IVUS image orientations, showing both vessel and catheter in their correct geometrical relationships.

1 Introduction

During the last decades, quantitative analyses from selective coronary contrast angiographic images have been established as de-facto standard for the diagnosis of coronary artery disease. Well-established systems for single-plane analysis of local stenoses have been complemented by accurate spatial reconstructions from biplane angiograms, allowing assessment of complex diffuse disease affecting the entire coronary artery system. However, the major limitation of X-ray angiography is its restriction to the inner lumen. The cross-sectional shape is mostly approximated by elliptical contours, and the wall thickness as well as the plaque composition cannot be determined at all. Recently, intravascular ultrasound (IVUS) of the coronary arteries evolved as an additional method in cardiovascular diagnosis. A catheter with an ultrasonic transducer in its tip is placed at the distal end of the desired vessel segment and pulled back with an approximately constant speed during imaging. The luminal cross-sections can be determined as well as the wall thickness, and even the composition of the plaque On the other hand, IVUS is not able to consider vessel curvature and torsion when assigning the detected plaque to specific locations. Spatial reconstructions as performed up to now by straight stacking of the images are geometrically incorrect and thus do not allow proper volumetric analyses.

Problem:

- Due to vessel *curvature*, the IVUS slices are not parallel. Thus, volume fragments at the inner side of the vessel related to its curvature will be overestimated and fragments on the outer side underestimated during volumetric analysis.
- Due to vessel *torsion* as defined by differential geometry, the axial orientation of an ideal IVUS catheter within the vessel is no longer constant. The torsion of the catheter path is zero only if the vessel lies within a plane. Whenever the vessel moves outside of this plane, the catheter twists axially, and this rotation must be considered in the 3-D reconstruction as well.

Solution: Combination of the data obtained from coronary angiography and intravascular ultrasound provides an exact assignment of the cross-sectional data to the vessel segment in both location and orientation.

2 Generation of Spatial IVUS Frames

- Basis for *geometrically correct 3-D reconstruction* of IVUS image sets,
- calculation of a *frame* for each IVUS image,
- 3-D catheter path used for derivation of spatial *location* and *orientation* of each IVUS frame.

2.1 Catheter Extraction

The imaging catheter is extracted in 2-D from the biplane angiograms by an dynamic programming approach (Fig. 4). Since sheathed catheters are used, the path at pullback start (i.e. in its distal position) corresponds to the path the transducer follows during the pullback.

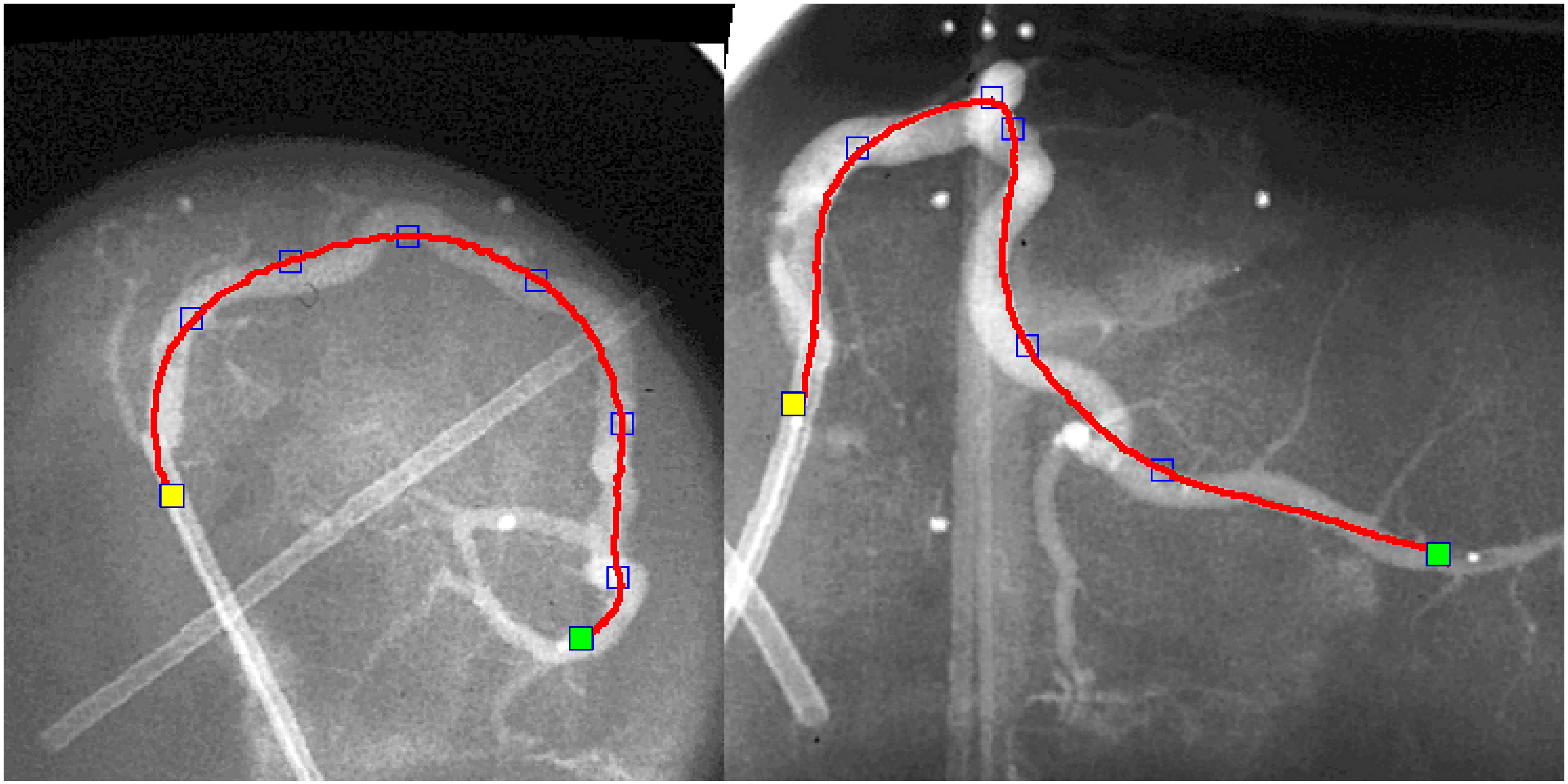

Figure 4: *Extraction of the Catheter Path* — transducer marked at the most distal position in both projections (green), along with presumed proximal end of the pullback (yellow), and some guide points outline the catheter path inbetween.

2.2 3-D Reconstruction of the Trajectory

After the catheter path is extracted, the *3-D trajectory* can be obtained:

- The initial imaging geometry is known from parameters determined from the gantry settings (Fig. 5a),
- some reference points (e.g. catheter markers, clips) are reconstructed and systematics in their errors (Fig. 5b) used for refinement of the imaging geometry [1],
- corresponding path elements are identified using the *epipolar constraint* and their 3-D coordinates calculated.

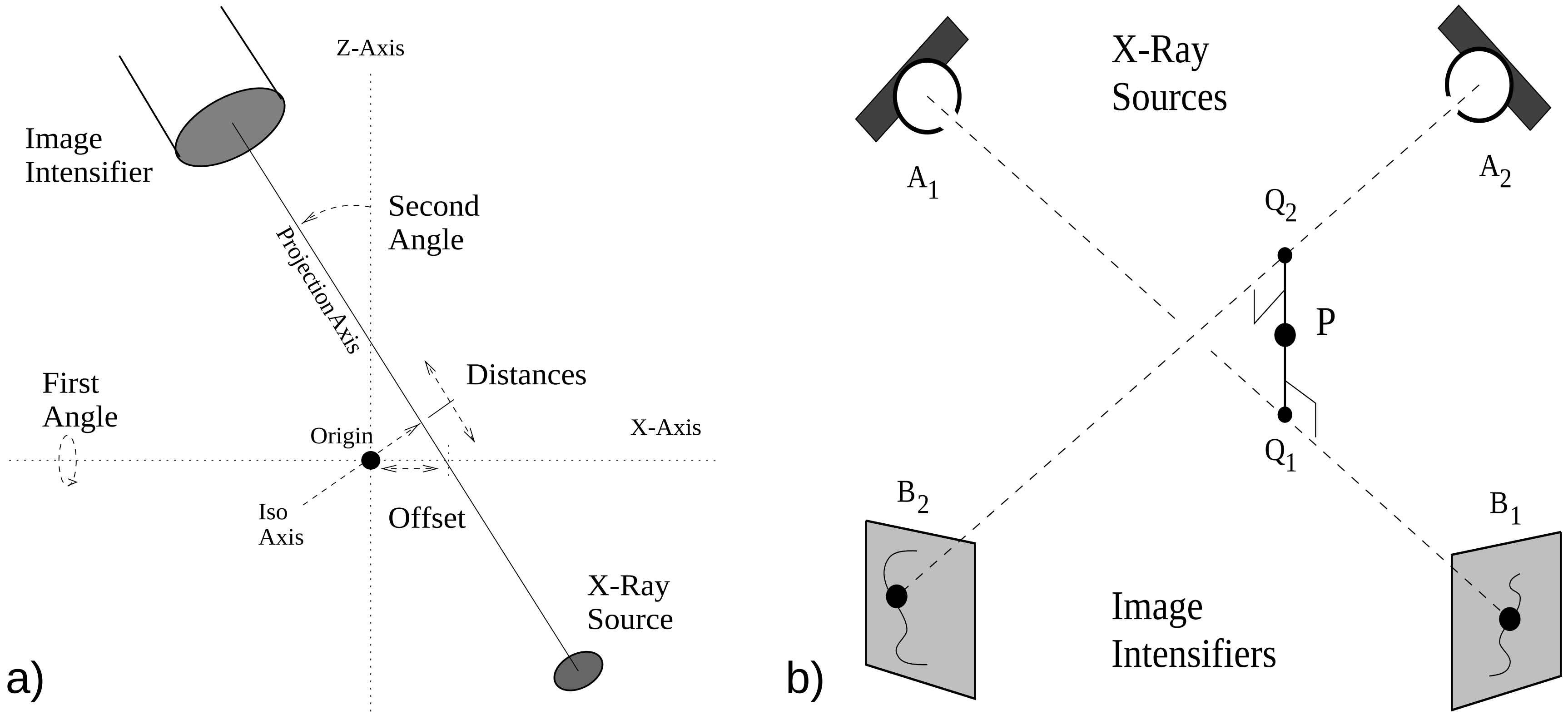

Figure 5: a) Degrees of freedom at a typical angiographic gantry setup; b) reconstruction of the 3-D coordinates of a single point P from its biplane projections B_1 and B_2, where the mismatch (i.e. distance $Q_1 - Q_2$) indicates the reconstruction error.

2.3 Mapping of the Image Locations

For each IVUS frame, its *location* has to be determined:

- Constant pullback speed is assumed, e.g. using automated devices,
- pullback length can be calculated from IVUS timestamp, thus
- actual location can be derived along the 3-D pullback path.

2.4 Calculation of Catheter Twist

The *relative orientation changes* between adjacent frames are calculated using our *sequential triangulation method* (Fig. 6) [3].

1. Use the three points of the catheter path next to the frames,
2. calculate circumscribing circle,
3. rotate previous frame around the normal n_i of the circle by the enclosed angle α_i.

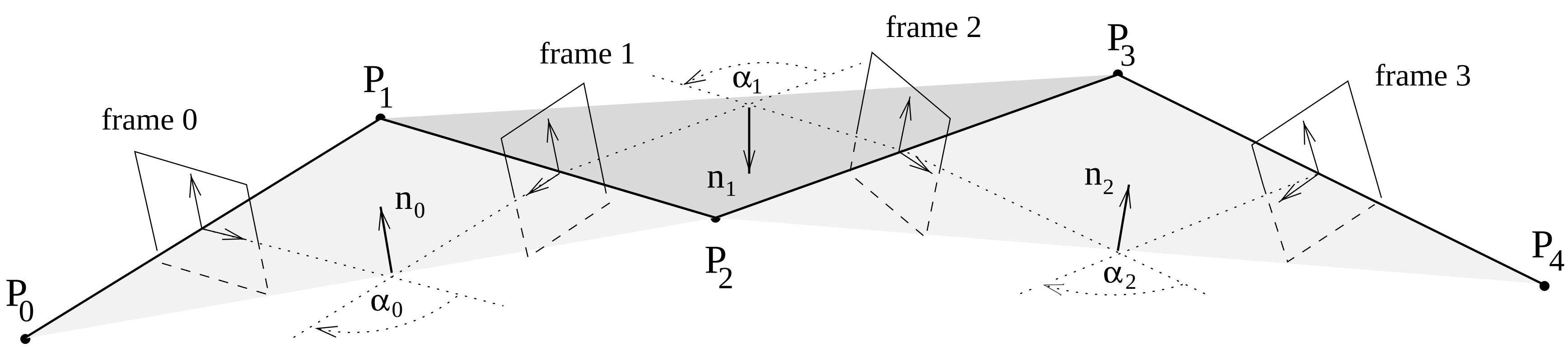

Figure 6: *Sequential triangulation method* for analytical determination of the relative orientation changes between adjacent IVUS frames.

2.5 Absolute Spatial Frame Orientation

- Sequential triangulation method delivers the *relative* orientation only,
- *leg-sock problem:* frame set (sock) may be rotated arbitrary around the catheter path (leg),
- natural landmarks like branches are often unreliable, artificial landmarks like clips not applicable in-vivo.

- The catheter always seeks a position of minimum bending energy within the vessel,
- *out-of-center location* of the catheter can be identified in both angiograms and IVUS images and used as landmark,
- two-stage optimization algorithm based upon statistics in moving windows along catheter path is used for minimization of axial error angles [5].

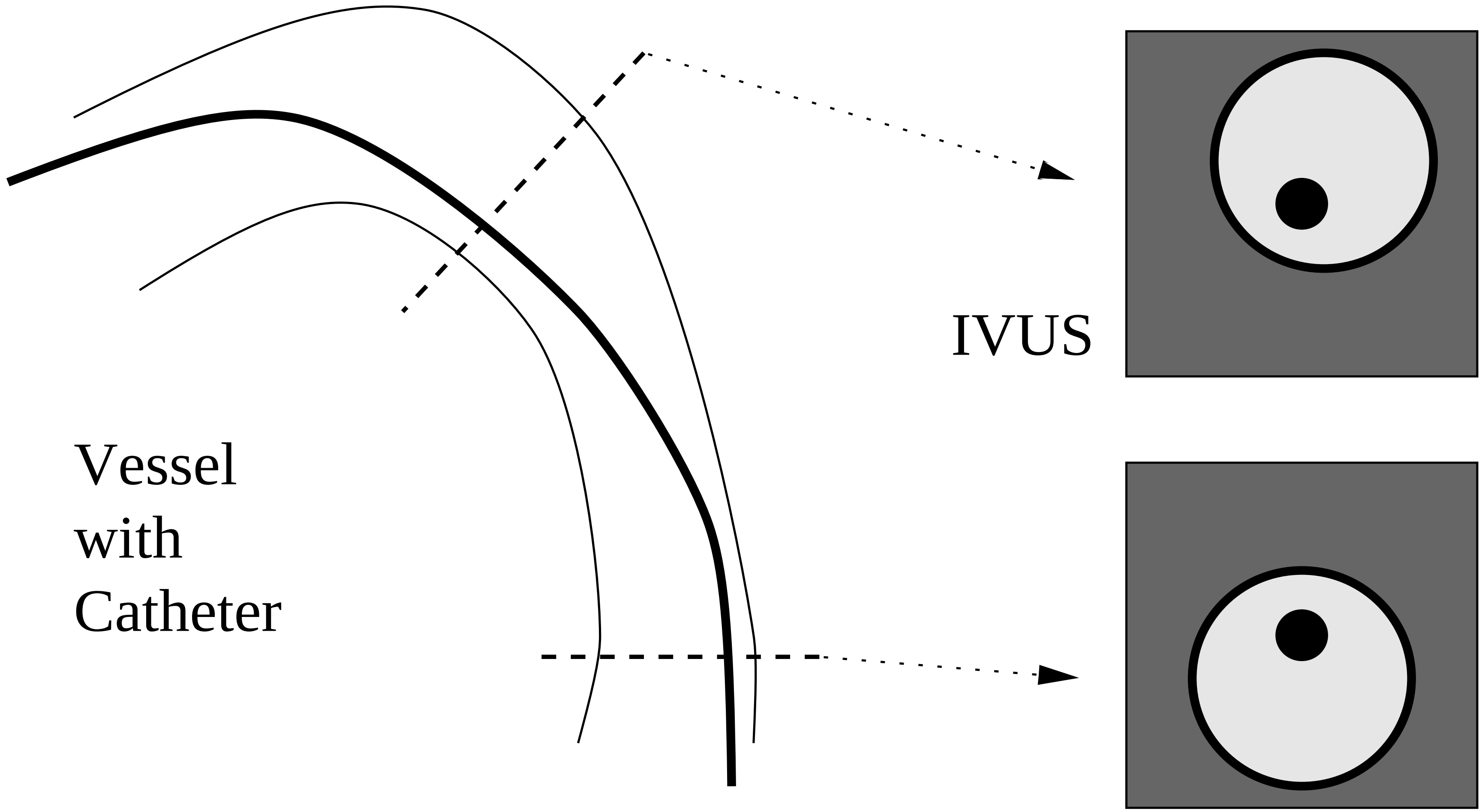

Figure 7: Theory of using the out-of-center location of the catheter as landmark for the absolute frame orientation.

3 IVUS Segmentation

IVUS image sequence is segmented by our well-established method described in [2], detecting the inner and outer borders of the vessel wall as well as plaque (if applicable):

- Automatic contour detection is based upon *graph search*,
- for the wall-borders, *edge triplets* are searched for, which represent the leading and trailing edges of the laminae echoes,
- an elliptic region of interest (ROI) is defined in the first image and adapted automatically for subsequent images,
- the user may interrupt at any stage to modify ROI boundaries in difficult images.

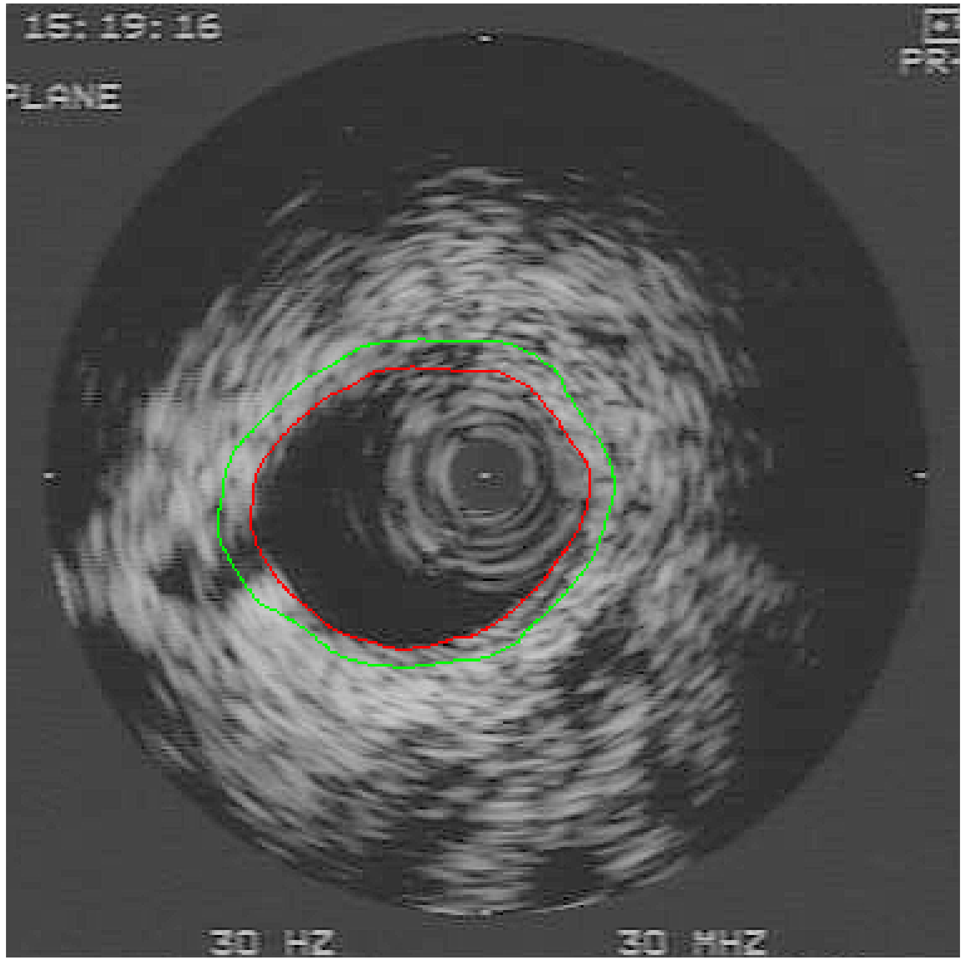

Figure 8: Determined contours of the inner (red) and outer (green) vessel wall borders.

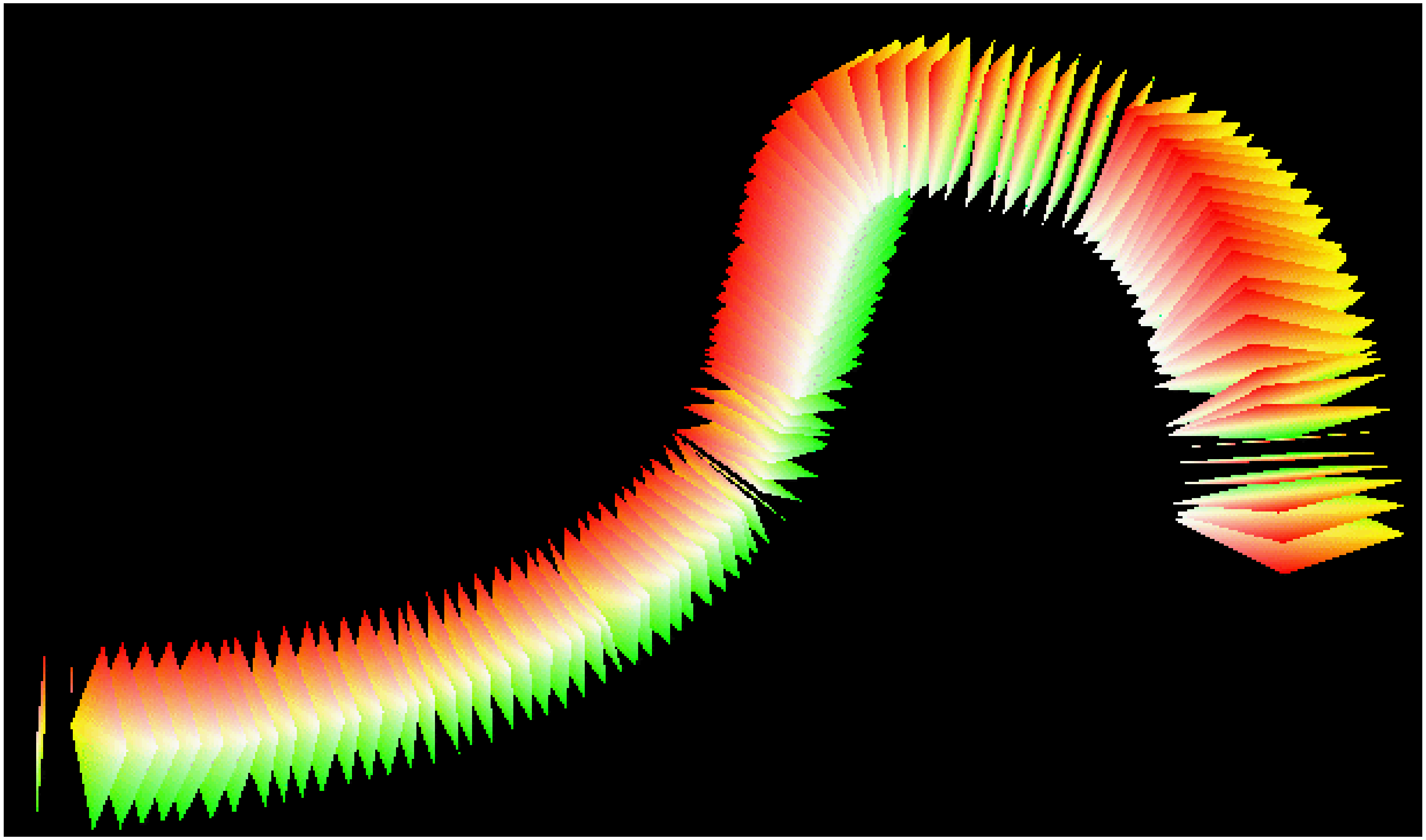

Figure 9: Calculated frames for the example shown in Figure 4; twisting can be seen from color-coded frame corners.

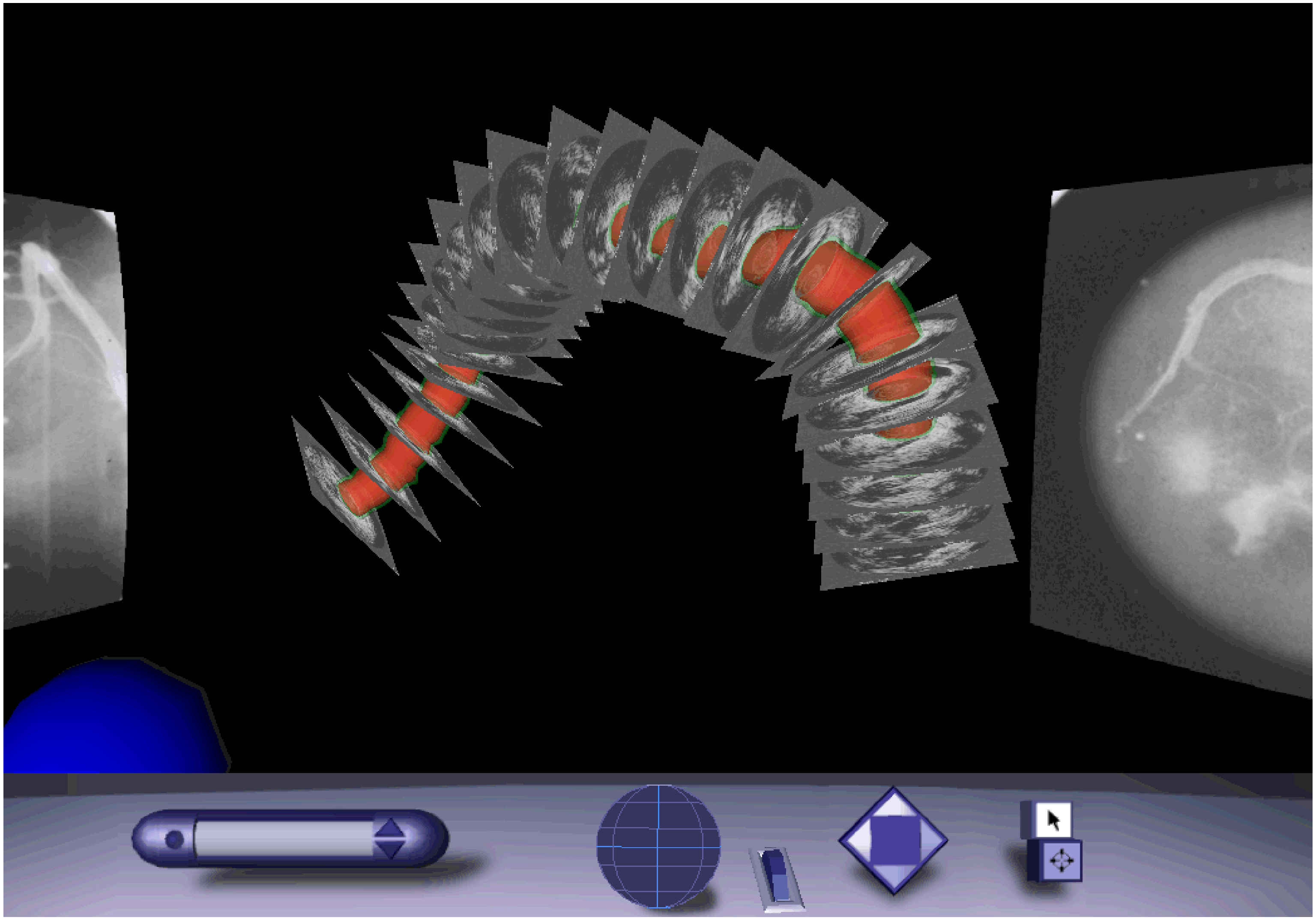

Figure 10: Visualization of the data shown in Figs. 1, 8 as an automatically generated VRML-2.0 model.

4 Validation

Validation in Computer Models:

- Using a chain of torsion-free *generalized joints*, any catheter path can be simulated in 3-D,
- reference coordinate systems can be calculated and used for estimating the reconstruction and mapping errors,
- highly tortuous paths can be generated and downsampled to angiographic resolution (Fig. 11a–c).

Validation in Cadaveric Pig Hearts:

- Right coronary arteries were supplied with *straightened paper clips* as visible references,
- clips were reconstructed from angiograms (Fig. 11d, e) and mapped into 3-D from IVUS images (Fig. 11f).

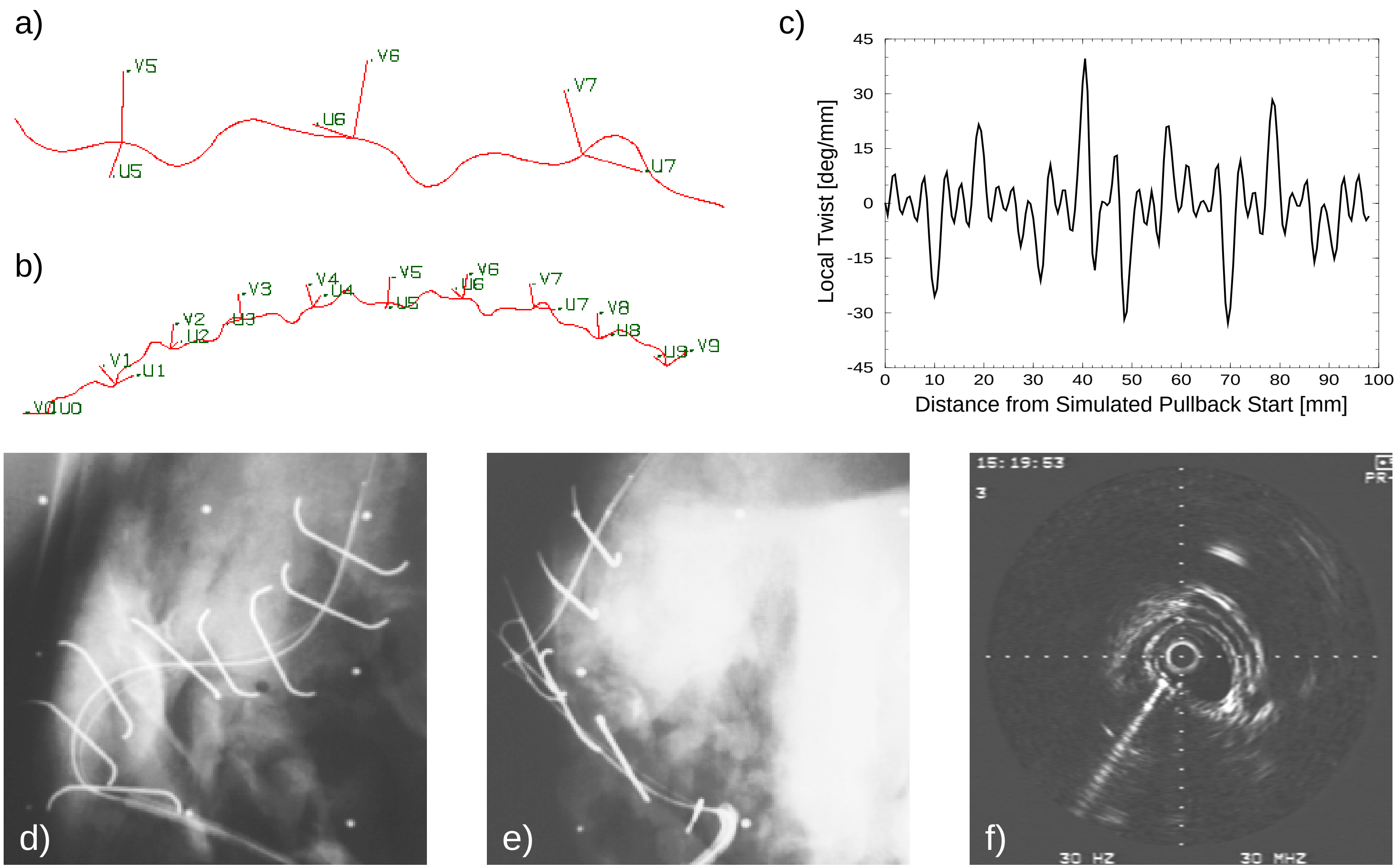

Figure 11: *Computer Model Generated from two Sine Waves* — (a) detail (b) full path (c) local twisting; *Pig Heart with Clips* — (d,e) angiograms (f) IVUS image.

5 Results

Evaluation of Computer Models:

- Using a small number (5) of joints with a reference frame between each pair, the matching error of the calculated vs. the reconstructed 2-D coordinate systems were less than 0.01°,
- placing a joint each 100 μm in the setup shown in Fig. 11a–c, the axial error after downsampling to 500 μm resolution over a length of 100 mm was RMS 1.05° (max. 2.52°).

Evaluation of Cadaveric Pig Hearts:

- A constant manual pullback speed of 1 mm/s was instructed,
- real pullback speed was estimated 1.14 ± 0.34 mm/s,
- RMS error in matched clips orientations over 6 pullbacks in 2 hearts was $21.96 \pm 4.87^\circ$.

Identified Error Sources:

1. The *manual pullback* introduces variations in the pullback speed and unsystematic twisting of the catheter [6],
2. the *mechanical setup* of the catheter system is subject to several forces (e.g. friction due to bending) leading to phase shifts and non-uniform image distortions.

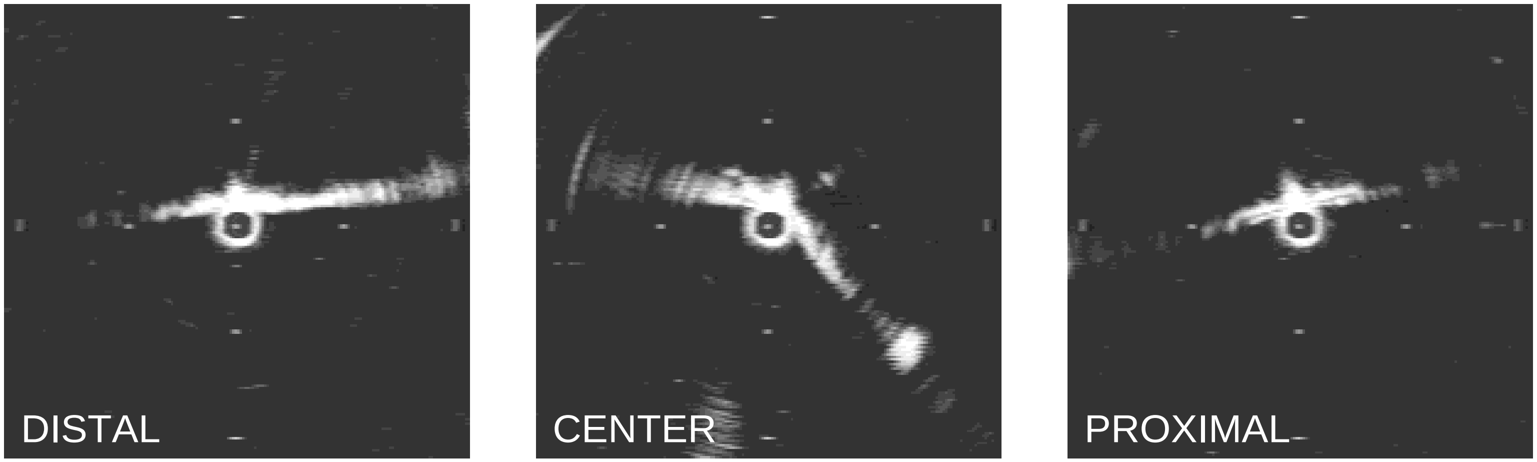

Figure 12: Catheter Bending in a tight curve (50° over 15 mm).

6 Conclusions

- Geometrically correct reconstruction of IVUS data by fusion with biplane angiography is feasible in good accuracy,
- spatially correct assignment of plaque and wall data as delivered by the IVUS segmentation allows realistic estimations in volumetry,
- geometrically correct 3-D IVUS reconstruction improves morphometric and hemodynamic analyses evidently,
- manual pullback is not suitable for fusion — *the use of an automatic pullback device is strongly recommended*,
- effects like phase shifts causing artificial IVUS image rotations have to be considered and corrected for — *part of the ongoing research*.

Further Reading

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[3] 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, no. 6, pp. 451–462, Dec. 1997.

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