Fusion for optimal path recovering in cerebral x-ray angiography

C. Boldak^{a,b}, C. Toumoulin^{b1}, J-L. Coatrieux^b

^{a,b}Polytechnic Institute of Bialystok, Department of Computer Science
Bialystok, Poland

^bLaboratoire Traitement du Signal et de l'Image, Université de Rennes1,
35042 Rennes Cedex, France

ABSTRACT

The objective is to extract the most plausible graph of two-dimensional vascular branches (e.g. with respect to some basic vessel features) or, in other words, to find the best pairing of vascular segments forming these branches. The assumption here is that a previous detection has been carried out which provides the vessel centrelines. The method, based on sparse to dense description, has been designed in order to eliminate irrelevant lines and to extract the most important branches. The key feature of the method is the use of data fusion concepts in a simple but efficient way, capable to later integrate possibilistic or fuzzy decisions. It makes use of local fusion decision at each node (vessel forking, crossing or ending), based on intensity, continuity and shape properties. Several criteria have been explored with hierarchically structured features. A global fusion allows multiple optimal paths to be set and further merged in order to derive a final graph. Local and global fusions are applied by traversing the vessel network from the extremities to the root and vice versa. Segments and branches are defined as objects for any further selection, manipulation and measurements. This method can be used both in pre-operative and intra-operative situations.

Keywords: X-ray angiography, branch formation, data fusion, Dijkstra algorithm

1. INTRODUCTION

The recent advances in medical imaging lead to a three-dimensional (3-D), high spatial resolution access of morphological and functional features of organs¹⁻². They provide larger and larger data sets, which impose to design either very fast automatic processing means or highly sophisticated interactive tools in order to face the clinical requirements. These new means apply to the all-anatomical structures including the vascular networks. If X-ray angiography provides a better resolution, both in space and time, than Magnetic Resonance Angiography (MRA) and Tomodensitometry (CTA), its main drawback is due to its 2-D nature and the difficulty to recover the 3-D structure from sparse (e.g. 2 or 3) projections. The place of X-ray angiography, if still of value for diagnosis purpose, is therefore evolving toward intra-operative use³.

In most of the surgical interventions for example, the critical issues concern the avoidance of the vessels but also fast on-site registration. They can be solved in a number of ways (external frames, surface features, positional imaging devices, etc.) but also through the acquisition of X-ray angiographic views and their matching to 3-D pre-operative data like MRA or CT volume. Instead of points, the most appropriate primitives to be matched are lines or curves (2-D and 3-D) which both can be extracted from the different data sets.

In this context, the whole process of image analysis has to be considered, including image calibration and distortion correction, detection/segmentation, feature extraction and matching, registration, visualization and so on. Many approaches can be followed to address each of these steps when dealing with vascular networks⁴⁻⁵. They must balance several requirements such as robustness to noise and shape variations, completeness of the extracted vessels, accuracy in localization, and computation time. If these requirements vary with the methodological or clinical objectives to be faced, whatever the imposed constraints, the major difficulties are related to the low signal to noise ratio, inhomogeneities due to the contrast medium into the vessels, crossing and superposition of vascular segments, the complexity of the network in 2-D views and the presence of pathological deviations.

¹ Correspondance: C. Toumoulin, E-mail: Christine.toumoulin@univ-rennes1.fr, Fax: 33 2 99 28 69 17, Tel: 33 2 99 28 62 20. Other authors: C. Boldak : E-mail : echo@ii.pb.bialystok.pl, Tel : 48 85 742 2041 ext. 308. J-L. Coatrieux: E-mail: Jean-Louis.coatrieux@univ-rennes1.fr, Tel: 33 2 99 28 16 93

The objective here is to extract the most plausible graph of vascular branches (e.g. with respect to some basic vessel features) or, in other words, to find the best pairing of vascular segments forming these branches. This work can be seen as an attempt to derive an intermediate description level where segments and branches can be considered as objects for any further selection, measurement or, more widely, manipulation⁶. The assumption here is that a previous detection has been carried out which provides the vessel centrelines. This problem can be addressed in various ways from mathematical morphology methods⁷, ridge and border tracking algorithms⁸⁻¹⁰, adapted filter, multiresolution approaches, up to deformable models¹¹⁻¹². Most often, the resulting features are incomplete (small or equivalently low contrast vessels remaining undetected) or include artefacts (due to other structures or imperfect subtraction) and these limitations must be taken into account in the subsequent processing stages as it is exemplified here. The present method has been designed therefore in order to eliminate irrelevant lines and to extract the most important branches with the following requirements in mind:

- A progressive, from sparse to dense, description of the vascular network based on a meaningful feature of the vessel segments, the length, instead of the calibre or the width;
- A control given to the user through a limited interaction as opposed to a fully automatic processing with the capability to preset parameters according to the a priori known viewpoints;
- A very low time computation to answer to the clinical constraints involved in intra-operative situations;

Another key feature of the method is the use of data fusion concepts in a simple but efficient way, capable later to integrate possibilistic or fuzzy decisions¹³⁻¹⁴.

2 FEATURING THE APPROACH

It can be schematically described as follows:

- Transform the input binary image into a set of segments. A segment is a fragment of a vessel limited in the 2-D projections by two extremities (e.g. nodes), each extremity being an ending point, a bifurcation point or a crossing point (a superposition with another, non connected vessel). Each segment can be described by its index number, an ordered list of pixels, the indices of its neighbouring segments at both extremities and some features or parameters;
- Choose the first, principal segment, so called “root”, which represents the origin of the arterial tree, and the other main segments, which are relevant enough to be included in the resulting network as far as they are connected to the “root”(they can be seen as a first sketch of the vessel graph). The selection of these segments can be achieved by means of either interactive, automatic or mixed procedures;
- Construct one path from each “main” segment to the “root”. Since a graph structure can contain loops (or cycles) and because multiple pathways can be found, some quality measures must be introduced to define the *best* one. These paths will share common segments;
- Build the final vessel graph. This stage relies on the criteria already used in the previous steps and allows to uniquely allocate the common segments to a given vessel branch. These branches are reconstructed by traversing the vessel network from the “root” toward the “main” segments.

Several frameworks can be derived at the fusion level, for instance:

- A local fusion: it can be stated by combining the local properties measured at each node resulting in a pairing decision. In that case any criteria related to intensity, continuity, shape features are merged into a decision function. This function can be a linear weighted sum or be obtained by some hierarchical, multi-level non-linear criteria. The best path, with respect to this function, can then be searched by means of an optimisation process;
- A global fusion: this second way consists to make use of a single property and to construct multiple optimal paths based on this property. The next step is then the fusion of these paths in order to derive a final graph.

Mixed schemes can be also designed from these two extreme situations. Only the latter option, with both forward and backward traversal, has been explored in this paper, our first objective being to compare the influence and the stability of the features used in the decision process and to produce a practical solution, even imperfect, to the problem at hands.

3. METHOD

3.1 Object-based image description

From the already extracted centrelines an object structure is generated. Each elementary vessel segment, delimited by bifurcation, crossing or end points, is identified; the list of consecutive pixels is stored, as well as the relational information given by its neighbours.

All points having only one neighbour are chosen as starting points. They are stored into a stack and from them; the tracking procedure leading to the segment formation is performed. As long as there exists only one connected pixel, it is added to the list and the length of the segment is increased. When an endpoint is found (no next point), the segment is stored. This procedure works until the stack is empty.

The bifurcation and crossing situations are recognized as pixels having more than one neighbour. Then, two (or three) new segments are created and the links between them and the ‘parent’ segment are established, their first points being stored in the above-mentioned stack as candidate starting points. In order to deal with potential cycles, it is checked at each node if the segment under study has not already been found (one of them is then removed and all corresponding connections are updated). When a segment has been completed, the stack of starting points is cleaned up.

A few features are then attached to each segment S_i :

- The length L_i corresponding to the number of pixels belonging to the segment;
- The directions (angles between the pseudo-tangent and, for example, the horizontal axis) α_{i1} , α_{i2} at each extremity of the segment; they are computed from straight lines defined over several horizons as follows:

$$\alpha_{i1} = \angle([P_{N-1} P_0], OX) \quad \alpha_{i2} = \angle([P_{L-N} P_{L-1}], OX) \quad (1)$$

with:

L : segment length

P_i : segment pixels, $i = 0 \dots L - 1$,

N : number of points used to estimate the angle (*angle depth*)

- Mean grey level G_i of M last (or first) segment pixels :

$$G_{i1} = \frac{1}{M} \sum_{j=0}^{M-1} I(P_j) \quad G_{i2} = \frac{1}{M} \sum_{j=0}^{M-1} I(P_{L-1-j})$$

Where $I(P_i)$ is the grey level at point P_i (in the original angiographic image).

These features provide more global descriptions (path length for instance) and allow to locally estimate similarity and continuity properties between pairs of segments at junctions through the following expressions:

- Total length of these segments $TL_{ij} = L_i + L_j$
- Difference between the directions of two segments $\Delta\alpha_{ij} = |\alpha_i - \alpha_j|$, taking the angles from the proper ends
- Difference between mean grey levels $\Delta G_{ij} = |G_i - G_j|$, at each forking or crossing nodes

3.2 Algorithm initialisation

The entire vessel network is defined with reference to the principal segment, so-called “root”, which is the parent of all segments in the image (Fig. 1). It is easily identified from spatial, shape, width and contrast considerations based on a priori

anatomical and image formation knowledge. So far, an automatic search among the set of segments is available as well as an interactive pointing procedure.

Figure 1. a) Schematic representation of a tree and b) of the root and main segments

The P longest segments are marked as “mains”. This parameter is a priori specified according to the image viewpoint but it can be interactively adjusted by the user in three ways: (1) by thresholding the segment length histogram, (2) by specifying the number P of desired segments and (3) by manually selecting or removing single segments with the mouse.

3.3 Path construction

This stage is aimed at the connection of each “main” segment to the “root” through the best (with regard to some criterion) path and, accordingly, at the construction of a tree-like structure, where each segment has its predecessor (parent) and its successor (child, if it is not the last branch), since the graph obtained in the previous stage can contain cycles.

To define a tree from a graph, one needs only to give to each segment, not disconnected from the “root”, the information about its parent. The strategy used to find the path between each segment and the principal one can be based on a distance or a cost function. Therefore, the problem is to find the best path in a graph between all segments and a given one. Many efficient algorithms can be found in the literature. The Dijkstra’s algorithm¹⁵ has been retained which, after replacing an ordinary linear collection (linear cost of some operations) by the heap data structure (logarithmic cost of all necessary operations (YYY)), allows to make it in $O(n^2)$ time. Several expressions have been derived for the cost function:

- Sum of the lengths of all segments S_i belonging to the path W connecting the segment S^* to the “root” T :

$$d_L(S^*, T) = \sum_{S_i \in W} L_{S_i}$$

- Sum of the angle differences for each pair S_i, S_j of neighbouring segments along the path W connecting a segment S^* with the principal one. This criterion is computed with several values (three will be used) of *angle depth to deal with potential local deformations*:

$$\sum_{\substack{S_i, S_j - \text{neighbours} \\ S_i, S_j \in W}} \angle \angle \angle$$

- Sum of the grey level differences in each pair of consecutive segments S_i, S_j belonging to the path W connecting the segment S^* under consideration to the “root”:

$$\sum_{\vec{i}} \textcolor{red}{\text{! ! !}}^{S_i, S_j \in W}$$

The application of the Dijkstra's algorithm, using these five cost functions, leads to five different tree structures (each segment has five parents – one for each criterion). To compile them into one, a voting mechanism has been designed. Going backward within the tree toward the “root” (in other words, from the “main” segments to the principal artery), a decision has to be taken at each node to specify the true parent segment. Different voting strategies have been implemented (refer to Section 3.5). At this stage, for any “main” segment, one and only one path leading to the “root” is obtained but these paths have usually common parts, as shown in Fig. 2.

Figure 2. Four paths from each main segment to the root

3.4 Graph building

In order to obtain the final graph, these common parts must be removed from all, except one path. This is achieved iteratively by traversing forward the tree (e.g. starting from the “root”). As long as the current segment belongs to more than one path, the next segment to the current one is chosen (the child segment). If all paths go by the same way, the choice is obvious. When a bifurcation or a crossing node is encountered, at least two groups of paths must be discriminated and each segment allocated to a given group. Here, the same voting mechanism is applied by using the previous criteria:

- Length; the segment which belongs to the path group containing the longest path is retained
- Angles; by minimising the $\Delta\alpha_{ij}$ estimated with different *angle depth* parameters
- Grey level; the minimum of ΔG_{ij} is looked for

When the current segment belongs to only one path, this path is stored as the resulting vessel branch. All its segments are being removed from other paths, while updating their lengths.

3.5 Decision strategies

These strategies employed in Sections 3.3 and 3.4 may use the five criteria (length, angles, grey level) in several ways. Deciding upon only one feature allows to examine its own performance with respect to the resulting tree. The partial or full combination of features is expected to perform better when local variations or errors may exist. A potential correlation between these features, if a priori known or learnt, can also be taken into account. This data fusion has been restricted here to a binary voting rule in order to avoid the construction of an heterogeneous function of the features where the component

weights are often arbitrarily or heuristically preset. However, the relations between features can lead to different groupings and multilevel decisions. Two schemes have been examined:

- All the criteria participate equally to the decision and the majority rule is applied: more importance is then implicitly given to the continuity property as expressed by the vessel segment ending direction
- A two-level decision structure is considered: a first vote is carried out by using the three angle criteria; the result is then combined with the two others (length and average grey level) to decide about the best pairing.

4. RESULTS AND DISCUSSION

The method has been applied to a series of 4 biplane angiographic images provided by the Radiology Department of the University of North Carolina at Chapel Hill¹⁶. The whole image acquisition protocol took place in operative room where the objective was to match and register the X-ray images with pre-operative computed tomography within the frame of an interactive guidance of surgical instruments.

A representative image is depicted Fig 3.a. All the images were pre-processed in order to detect the vessel centrelines using adapted filtering¹⁷ (Fig 3.b).

Figure 3. a) Original angiography, b) Grey level centrelines got from an adapted filtering based process¹⁷

They clearly displayed the difficult situations mentioned above: superposition (especially in the interhemispheric plane), non-connected lines due for instance to subtraction errors, etc.... These images do not show details about local configurations where discontinuities in direction, non-exact match corresponding to crossings often occur. They could be caused by imperfections in the detection but also related to classical issues in X-ray images (small and large vessel junctions, non-uniform distribution of dye product,).

The next pictures depict the behaviour of the several criteria and the different fusion schemes applied as well as the resulting graphs. These images have been obtained with the following parameter values: $P = 100$, N (angle depth) = 5, 10, 15 and M (grey level horizon) = 10.

The method has been developed on a Pentium III 450 Mhz using Visual C++ 6.0. The user interface includes a number of functionalities like multiple image display and overlay, high resolution image zooming (in order to explore details of local behaviours), histogram handling with interactive thresholding, colour-based vessel identification, statistical analysis of votes over the whole or part of the images, ... The most important functionality, however, is provided by an elaborated pointing system which allows to delete or recover vessel segments, but more importantly, to examine in-depth the all features related

to a segment (parameters and neighbours), a junction (for instance the corresponding votes), and to a path (set of segments with the related costs). Several tests have shown that the results are obtained almost immediately.

Figure 4. a) Binary centrelines and retained segments (100 in dark blue) through a length thresholding,
b) Paths resulting from angle criterion (dark blue: non-connected segments),
c) Paths resulting from length optimisation,
d) Paths obtained when fusing length, angle and direction criteria

The images displayed Fig. 4 depict that the different criteria lead to the coherent extraction of the largest vessel with some variations around the most sinuous segment. Vessels with similar widths mainly form the remaining part of the network, by segments of comparable lengths. The differences resulting from the use of a unique parameter (angle Fig. 4b), length optimisation (Fig. 4c) and the full fusion (Fig. 4d) are not so significant. They appear mainly between Fig. 4c and the two others: the shortest path does not provide the best association when applied to 2-D images. The pairing obtained by using the continuity in direction is a step forward and the combination of short, medium and large horizons allow to correct local estimation biases. Fusing the criteria provides a better association of segments with respect to anatomical-based descriptions. However, there is no guarantee of an exact matching due to the intricate appearance of the network, and subsequently the difficulties to estimate the features characterizing the vessel segments.

These results show that a high dependence still remains with the pre-processing step aimed at the detection of centrelines. It can be thought, from the example given here, that there is too much information in the binary image to build consistent paths. A multiresolution scheme would be of little help due to the similar sizes of the vessels. The only degree of freedom is then coming from the initialisation stage where the number of segments can be interactively defined. The choice of the longest vessels is well founded because the peripheral vessels are first included. Then a progressive inclusion of non-selected segments can be envisaged as far as they are potentially concerned with the path search to the root. The voting

procedure operates as some kind of compensation of local measurement biases (more sensitive when dealing with directions and mean grey levels). Other features could be examined: width for instance is highly correlated to the ridge grey level and their precise estimation assumes that a robust border detection scheme is available; curvature smoothness of the centrelines, when computed over short lines, is unlikely to bring additional cues. Another way capable to improve the present method consists to change the categorical decision process into a probability, possibility¹⁴ or plausibility¹³ frame. The latter for instance requires the definition of some probability masses, which can be defined from the features already used here. The combinatorial problem intrinsic to the theory of evidence is not relevant in the present case if the set of hypotheses is reduced to local or limited neighbourhood pairings. Such frames therefore represent a natural extension of this work.

5. CONCLUSION

The method described in this paper points out that the formation of vascular branches, or better said, sets of segments, can be performed in an efficient way and that the resulting object-based representation is well suited for subsequent handling aimed at image matching and registration. The interactive control of the graph can be used to progressively refine these further steps and lead to sparse-to-dense processing. These results show however that quantitative local features and the global optimisation process do not guarantee soundness with respect to anatomical concerns as they could be appreciated by visual inspection. Pairing decisions are however quite stable and coherent both intra- and inter-images. The present method can be easily extended to 3-D data while keeping a very low time computation, which is of critical importance when considering very large data volume.

ACKNOWLEDGEMENTS

We are grateful to S.M. Pizer, E. Bullitt and L. Ibanez for their welcome of C. Toumoulin in the Department of computer Science, University of North Carolina, Chapel Hill and the many fruitful discussions as well as the support provided for the image data.

REFERENCES

1. J.L. Coatrieux, C. Roux, *Biomedical imaging: integration of image engineering, biology and medicine*, In: Contemporary Perspectives in Three-dimensional Biomedical Imaging, C.Roux and J.L.Coatrieux Eds, IOS Press, pp 3-27, 1997.
2. V. Burdin, B. Solaiman, C. Toumoulin, J-L. Dillenseger, J-J Jacq, C. Roux, *Image Processing Paradigms in Medicine*, In: Biomedical Imaging IV, IEEE EMBS Summer School Book Series, C.Roux and J.L.Coatrieux Eds, IEEE Press, 2000.
3. S. Lavallée, P. Cinquin, J. Troccaz, *Computer Integrated Surgery and Therapy: State of the Art*, In: Contemporary Perspectives in Three-Dimensional Biomedical Imaging, C.Roux and J.L Coatrieux Eds, IOS Press, pp 239-309, 1997.
4. J-L. Coatrieux, M. Garreau, R. Collorec, C. Roux, *Computer Vision Approaches for the Three Dimensional Reconstruction of Coronary Arteries: Review and Prospects*, Critical Reviews in Biomedical Engineering, 22,1, pp 1-38, 1994.
5. C.J. Henri, T.M. Peters, *Three-dimensional reconstruction of vascular trees. Theory and methodology*, Med.Phys, 23,2, pp 197-204, 1996.
6. C. Toumoulin, F. Mao, *Spatio-temporal grouping for the formation of vascular segments in coronarography image sequences*, Health Care Technology, 5, pp 383-406, 1997.
7. C. Toumoulin, R. Collorec, J-L. Coatrieux, *Vascular network segmentation in subtraction angiograms: a comparative study*, Med.Inform, 15, 4, 1990.
8. Y. Sun, *Automated identification of vessel contours in coronary arteriograms by an adaptive tracking algorithm*, IEEE Trans. Medical Imaging, 8, 1, 1989.
9. M. Sonka, M.D. Winniford, S.M. Collins, *Robust simultaneous detection of coronary borders in complex images*, IEEE Trans. Medical Imaging, 14, 1, pp 151-161, 1995.
10. M. Sonka, G.K. Reddy, M.D. Winniford, S.M. Collins, *Adaptive approach to accurate analysis of small-diameter vessels in cineangiograms*, IEEE Trans.Medical Imaging, 16, 1, pp 87-95, 1997.

11. A.K. Klein, F. Lee, A.A. Amini, *Quantitative Coronary Angiography with Deformable Spline Models*, IEEE Trans.Medical Imaging, 16, 5, pp 468-482, 1997.
12. T. McInerney, D. Terzopoulos, *Topology Adaptive Deformable Surfaces for Medical Image Volume Segmentation*, IEEE Trans.Medical Imaging, 18, 10, pp 840-850, 1999.
13. G. Shafer, *A Mathematical Theory of Evidence*, Princeton University Press, Princeton, NJ, 1976
14. H. Prade, *A computational approach to approximate and plausible reasoning with applications to expert systems*, IEEE Trans.Pattern Anal. Mach.Intell, 7, 3, 1985.
15. E.W. Dijkstra, *A note on two problems in connexion with graphs*, Numer. Math., October, 1, pp 269-271, 1959.
16. A. Liu, E. Bullitt, S.M. Pizer, *Surgical Instrument guidance using synthesized anatomical structures*, CVRMed-MRCAS'97, Springer Verlag, 1205, pp 99-108, 1997.
17. S. Ruan, A. Bruno, R. Collorec, J-L. Coatrieux, *Estimation de mouvement 3D en coronarographie*, Actes 13^{ieme} Colloque GRETSI, Juan les Pins, pp 801-804, 1991.