Automatic construction of minimal paths in 3D images: An application to virtual endoscopy

T. Deschamps[a,b], J.M. Létang[a], B. Verdonck[b] and L.D. Cohen[c]

[a]Laboratoires d'Électronique Philips, *(Email: {deschamps,letang}@lep.research.philips.com)*
22, Avenue Descartes, B.P. 15, 94453 Limeil-Brvannes Cedex, France

[b]Philips Medical Systems Nederland B.V., EasyVision Advanced Development,
P.O. Box 10.000, NL-5680 DA Best, The Netherlands

[c]Laboratoire Cérémade, Université Paris IX Dauphine,
Place du Maréchal de Lattre de Tassigny, 75775 Paris Cedex 16, France

Manual path definition for guiding virtual endoscopy is a very tedious task for human operators. In this paper we present a 3D path tracking routine to build trajectories inside tubular anatomical objects with minimal user interaction. The algorithm determines the "shortest" path between two user indicated points (start and end points).

This method, based on the level-set formalism, efficiently solves the shortest path problem using the so-called "fast-marching" algorithm. The method is illustrated for colon and blood vessel tracking.

1. INTRODUCTION

The visualisation of volumetric medical image data is crucial for diagnosis and therapy planning. Different possibilities for this visualisation exist: 2D grey value reformat views (see figure 1), maximum intensity projection (MIP, and its variants), shaded surface displays, volume rendering, virtual endoscopy... Basically, virtual endoscopy allows to visually inspect regions

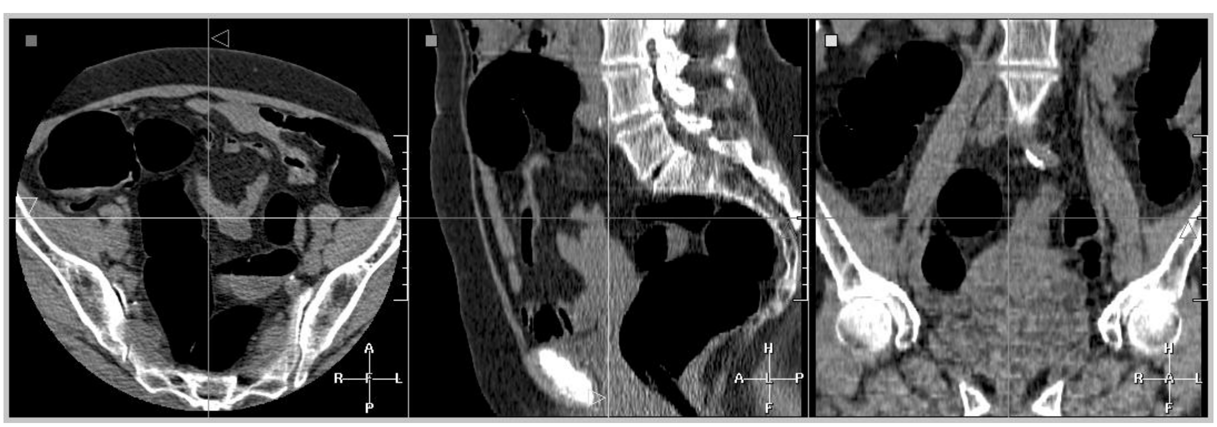


Figure 1. Three orthogonal views of a volumetric CT data set of the colon.

of the body that are dangerous and/or impossible to reach physically (e.g. behind an airway stenosis or obstruction).

Virtual endoscopy creates perspective views of the inside of tubular structures of human anatomy. This allows the clinician to view the anatomy in a comfortable way, immediately after data acquisition, thus revealing complex anatomical relations almost instantly. A virtual endoscopic system is usually composed of two parts:

1. Path construction, the successive locations of the flight through the tubular structure of interest;
2. Three dimensional interior viewing along the endoscopic path. Those views are adjoined creating an animation which simulates a virtual fly-through. The views are usually created using surface shaded rendering or volume ray-tracing.

A major drawback in general remains when the user must define all path points manually. For a complex structure (small vessels, colon,...) the required interactivity can be very tedious. If the path is not correctly built, it can cross an anatomical wall during the virtual fly-through. Path construction in 3D images is thus a very critical task and precise anatomical knowledge of the structure is needed to set a suitable trajectory.

Our work focuses on the automation of the path construction, reducing interactions and improving performance, in a robust way, given only two end points and the image as inputs.

2. AUTOMATIC PATH CONSTRUCTION

We derived an automatic path tracking algorithm in 3D images, by mapping this path tracking problem into a "shortest" path problem between two fixed end points. Defining a cost function inside an image, the "shortest" path becomes the path for which the integral of the cost between the two end points is minimal. Cohen and Kimmel [1] solved the minimal path problem with a front propagation equation, starting from a given initial front. This equation is derived from the *Eikonal* equation [2] (that physically models wave light propagation). The definition of the cost function and the properties of the desired path must be related to the image and object characteristics, keeping in mind the suitability for virtual endoscopy.

Therefore, the first step is to build an image-based measure that defines the minimality property in the studied image, and to introduce it in the *Eikonal* equation. According to this measure, a front is propagated on the entire image domain, starting from an initial front restricted to one of the fixed points. The arrival times calculated at each point of the front in the image domain with the *Eikonal* equation correspond to the integrated cost. The propagation process is stopped once the second fixed point is reached. The resulting integrated cost map (time-of-arrival map) is convex and shows only one global minimum: the start point. Obtaining the shortest path between any point (and in particular the second fixed point) and the first fixed point is simply done by using a gradient descent technique, until the first point is reached.

A method to propagate this front in a quick and efficient way was proposed by Sethian, [2]. The algorithm, called *fast marching*, quickly solves the front propagation problem. The key idea is to deal with voxels which are close to the current front during its propagation, the so-called *narrow band* set of voxels. This propagating set of voxels is shown in figure 2 for the colon, for which the original CT data is displayed in figure 1. A numerical scheme was implemented to propagate this higher dimensional function. A particular data structure, called "min-heap", was

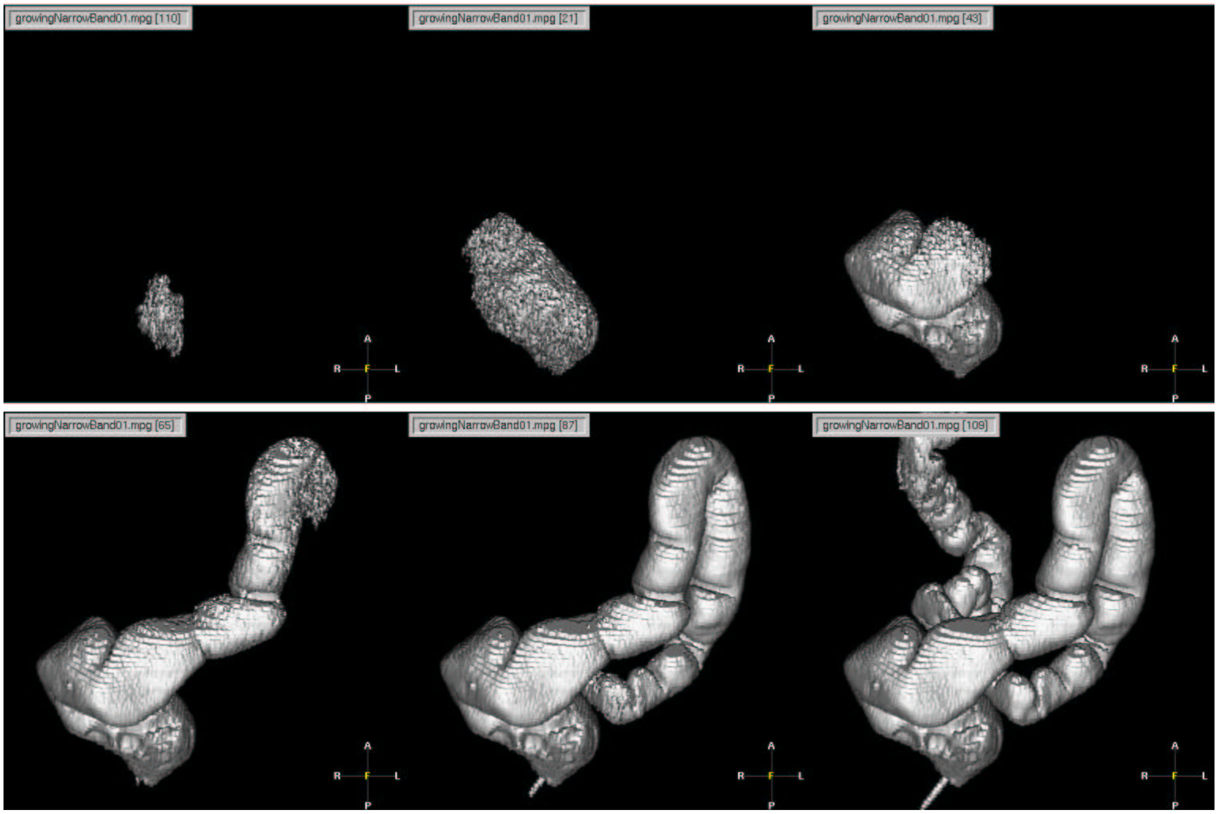
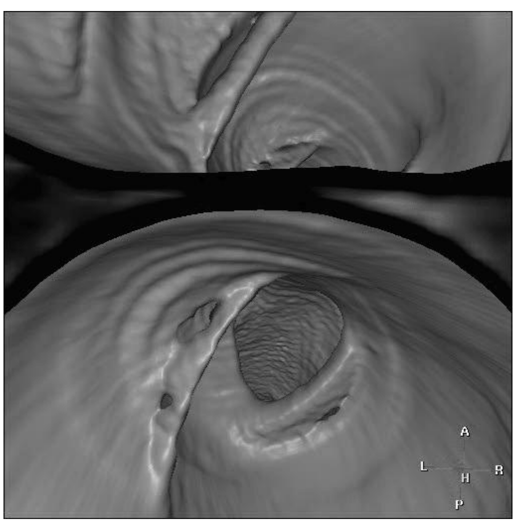


Figure 2. Propagating front inside the colon (original CT data displayed in figure 1).

used to store the *narrow band* points and to efficiently locate at each step of the propagation the voxels that are in the region of interest (see [3] for details).



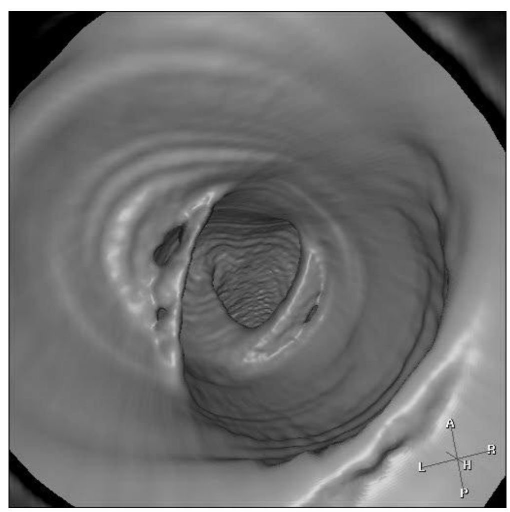
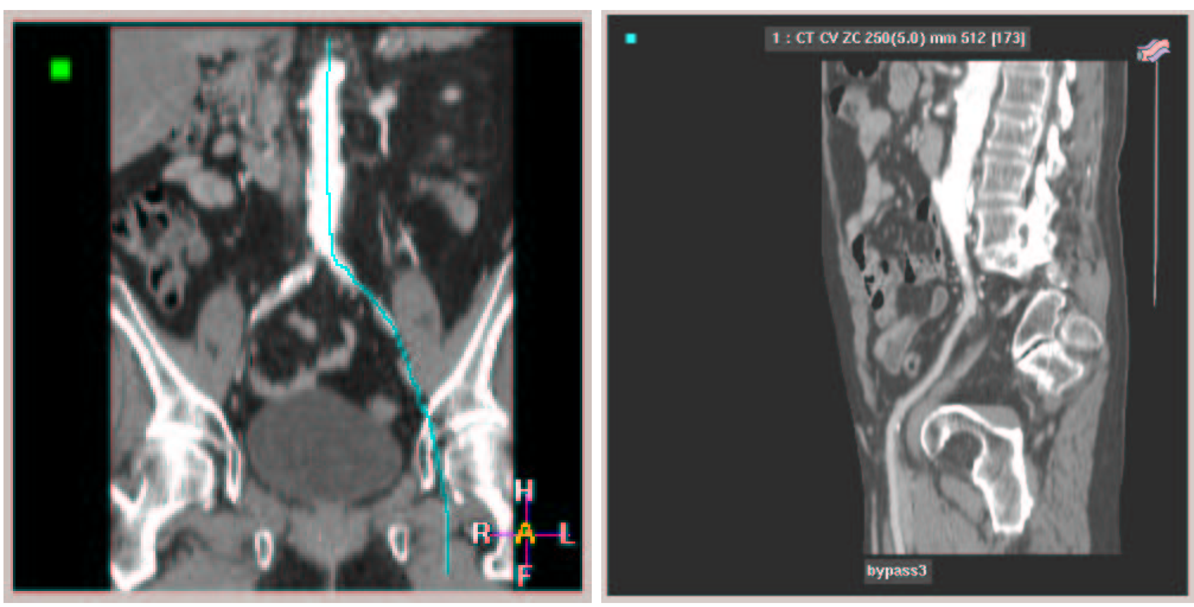


Figure 3. Inside view of the colon using perspective volume rendering on the EasyVision workstation. Path badly centred in the U-turn (left). Optimal centring (right).

The front propagates faster in low-cost regions. This means that particular attention is necessary to design the cost function so as to be lower along the tubular structure, and higher elsewhere, especially when crossing the borders. This can be achieved by building a cost function based on gradient and/or grey level information. Thresholding is usually sufficient to provide a uniform measure within the tubular structure. The shortest path produced in such a situation will be very close to the object walls around each path turn, as shown on figure 3-left, since the measure does not contain any information on the relative position with respect to the object walls. However, the desired endoscopic path should remain in the centre as shown in figure 3-right. A series of solutions can be suggested: path centring in slices perpendicular to the path, calculation of a distance map (by chamfer distance transforms or fast marching starting from the object edges) and path tracking through the inverse distance cost volume or morphological thinning of the segmentation.

3. RESULTS

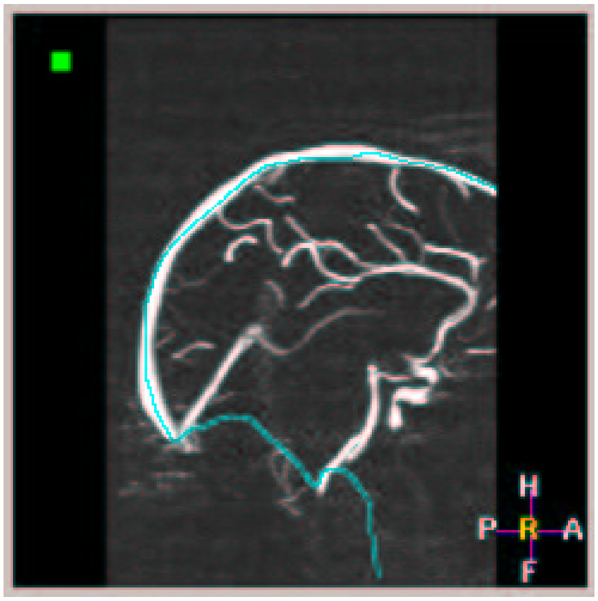
A test was made on an aorta CT scan, as shown in figure 4. In this case the propagation measure is based on a nonlinear function of the intensity of the contrast solution that fills the aorta. However, we must be aware that this intensity is not entirely reliable since the contrast bolus dilutes during the acquisition time. Thus, the tracking procedure could be disturbed, e.g. allowing the path to cross other anatomical structures with similar intensities. We made a test in the external iliac artery. Figure 4-left shows a reformat CT view along with the detected path. The curved reformat view along this path in figure 4-right shows that it was correctly recovered even if the contrast of the iliac artery is very low. We can also notice in this figure the extent of the intensity variations along the path.



Coronal reformat CT view + path — Sagittal curved reformat view

Figure 4. Path tracking in aorta inside a CT volume.

Figure 5 shows an example on brain vessels in a MRA scan. As compared to the previous example, we now have no longer any perturbing structure in the background, however the spatial resolution is lower. We propose here to track the superior Sagittal sinus, using a nonlinear function of the image dye intensity. The detected path is displayed in figure 5-left superimposed on a MRA projection image (partial MIP). A curved reformat view along the path is displayed in figure 5-right, showing that the detected trajectory correctly fits inside the canal.



Sagittal reformat MRA projection + path

Coronal curved reformat view.

Figure 5. Path tracking in brain vessels in a MRA volume.

4. CONCLUSION

In this paper we presented a fast and efficient algorithm that computes an optimal 3D path between two user-entered points. The results are promising for several clinical applications, including those dealing with very complex topology, especially for the guidance of endoscopic viewing. The success of the tracking approach for objects with non-uniform grey-level contrast depends on the appropriate design of the cost function. Nevertheless, the method provides an efficient and robust alternative to the manual path construction and will be further clinically validated.

REFERENCES

1. L.D. Cohen and R. Kimmel. Global minimum for active contour models: A minimal path approach. *International Journal of Computer Vision*, 24(1):57–78, 1997.
2. J.A. Sethian. *Level set methods:Evolving Interfaces in Geometry, Fluid Mechanics, Computer Vision and Materials Sciences*. Cambridge University Press, University of California, Berkeley, 1996.
3. R. Sedgewick. *Algorithms in C - Parts 1-4*. Addison-Wesley, Reading, Massachusetts, USA, 3 edition, 1998.