Enhanced Segmentation and Skeletonization for Endovascular Surgical Planning

Irene Cheng, Amirhossein Firouzmanesh, Arnaud Lelevé, Rui Shen, Richard Moreau, Vicenzo Brizzi, Minh Tu Pham, Patrick Lermusiaux, Tanneguy Redarce, Anup Basu

► **To cite this version:**

Irene Cheng, Amirhossein Firouzmanesh, Arnaud Lelevé, Rui Shen, Richard Moreau, et al.. Enhanced Segmentation and Skeletonization for Endovascular Surgical Planning. SPIE 2012, Feb 2012, San Diego, United States. pp.83162W, 10.1117/12.911090 . hal-00703244

HAL Id: hal-00703244

https://hal.science/hal-00703244v1

Submitted on 21 May 2015

Enhanced Segmentation and Skeletonization for Endovascular Surgical Planning

Irene Cheng[a,b], Amirhossein Firouzmanesh[a], Arnaud Leleve[b], Rui Shen[a], Richard Moreau[b], Vicenzo Brizzi[b], Minh-Tu Pham[b], Patrick Lermusiaux[b], Tanneguy Redarce[b], Anup Basu[a]

Department of Computing Science, University of Alberta, Edmonton, AB T6G 2E8, Canada
INSA, Lyon, France; and CHU Lyon, France

ABSTRACT

Endovascular surgery is becoming widely deployed for many critical procedures, replacing invasive medical operations with long recovery times. However, there are still many challenges in improving the efficiency and safety of its usage, and reducing surgery time; namely, regular exposure to radiation, manual navigation of surgical tools, lack of 3D visualization, and lack of intelligent planning and automatic tracking of a surgical end-effector. Thus, our goal is to develop hardware and software components of a tele-operation system to alleviate the abovementioned problems. There are three specific objectives in this project: (i) to reduce the need for a surgeon to be physically next to a patient during endovascular surgery; (ii) to overcome the difficulties encountered in manual navigation; and, (iii) to improve the speed and experience of performing such surgeries. To achieve (i) we will develop an electro-mechanical interface to accurately guide mechanically controlled surgical tools from a close distance, along with a 3D visualization interface; for (ii) we will replace the current surgical tools with an “intelligent wire” controlled by the electro-mechanical system; for (iii) we will segment 3D medical images to extract precise shapes of blood vessels, following which we will perform automatic path planning for a surgical end-effector.

Keywords: Endovascular surgery, blood vessel segmentation, surgical path planning

1. INTRODUCTION

Endoscopic surgery, also known as Minimally Invasive Surgery (MIS), is becoming widely deployed to replace classical surgery in order to reduce the recovery time and improve patient safety. However, there are still many challenges in improving the safety of doctors as well as patients, and reducing surgery time; namely, regular exposure to radiation, need for heavy cumbersome protective clothing covering only certain parts of the body, lack of real-time interactive 3D visualization, and automatic planning and tracking of a surgical end-effector. Improvements in equipment and technique have been made, resulting in routinely high procedural success, and being safer and more effective for patients, while also making the procedure itself technically easier and quicker for the operator [10]. Endoscopic procedures can be done to make a diagnosis, a biopsy, a surgery, etc. According to the area affected, endoscopy can also be called (non exhaustive list):

- Laparoscopy (the abdominal cavity)
- Thoracoscopy (the thorax area)
- Arthroscopy (the joints surfaces, cartilage, and ligaments)
- Rhinoscopy (the nose, nasal turbinates, frontal sinuses)
- Otoscopy (the external ear)

- Cystoscopy (the urogenital organs – vagina, bladder, urethra)
- Endovascular surgery (the blood vessels, the aorta)

Generally, the system developed is specific to the medical intervention; but, for a state-of-the-art about the actuators/sensors used, any procedures can be considered. In the literature, several solutions to enhance endoscope operability are available. Classical solutions are based on wire-driven robots. The main issue concerning wire-driven endoscope is the difficulty in identifying the friction phenomenon of the wires. Thus, the control may not be as accurate as desired. Usually, a wire-driven technology enables only the control of an endoscope tip. One solution is to assemble several independent units in a serial configuration, which results in greater design complexity. For example, Zhang et al. proposed a six degrees of freedom (dof) endoscope for fetal MIS [18]. It is composed of 3 units of 2 dof each in order to obtain a 6 dof endoscope. Since the wire has to go through the different units, there may be interference between them. The paper also proposed to estimate the contact force by measuring the wire tension. Other solutions have been developed to offer more possibilities of controlling the endoscope tip. For instance, a continuum robot based on bellows has been developed in order to place an endovascular stent to solve aortic aneurysm [4]. Another kind of actuator is proposed in [12] where authors present an “inch worm” system with three inflatable balloons to move itself inside a tube. Whereas the previous systems ensure only the orientation of the endoscope tip, this system also ensures the endoscope displacement through a tube such as a vessel for instance. The principle is based on the McKibben pneumatic artificial muscles: when the bladder is inflated, the mesh expands radially, but contracts along its length. The main drawback of this technology is the permanent contact exerted on the tube inside which it moves.

One of the issues in developing an active endoscope is the limited space available for the actuators. To deal with this issue, De Sars et al. proposed an active endoscope based on Shape Memory Alloy (SMA) [16]. It is based on the same principle as the wire driven endoscope but some SMA wires are attached to the wires to ensure the bending of the endoscope tip. In [17], authors present a system to control the location of the endoscope tip by magnetic levitation. Magnets are embedded in the endoscope and generating a magnetic field creates magnetic forces to attract or repel the endoscope tip.

All these solutions bring some benefits in endoscopic procedures such as accuracy of the position control, enhancement of the catheterization through complex anatomy, enhancement of the stability, increase of the operator comfort, reduction of the exposure for the operator. These systems also bring some limitations, such as the cost of the system and the need for surgeons to acquire new skills. However, one of the main issues lies in the lack of tactile feedback for the operator [2]. Some researchers try to solve this issue by proposing the development of miniaturized force sensors [6,8], a stiffness control [11], or force estimation [18]. Enhancement can also come from the 3D visualization. Indeed, it can be used to allow surgeons to locate their tools inside a patient’s body and to have position or force feedback.

The focus of our project is on endovascular surgery and the challenges related to it. Thus far we have enhanced 3D segmentation of blood vessels by a process of initialization of 2D livewires in two orthogonal directions. We have also been able to extract robust 3D medial axes for smooth end-effector trajectory planning by using a new scale-space skeletonization algorithm. The remainder of this paper is organized as follows: Section 2 reviews various methods for blood vessel segmentation. An overview of our approach is given in Section 3. Section 4 presents experimental results, before the work is concluded in Section 5.

2. REVIEW OF BLOOD VESSEL SEGMENTATION

Radiologists have progressively adopted vascular segmentation techniques to explore the 3D morphology of vessels or other tissues. A 3D representation of vasculature has actually become necessary in image-guided neurosurgery and pre-surgical planning [7, 15]. Medical image treatments form an essential step in solving several practical applications such as diagnosis of the vessels (e.g., stenosis or malformations) and registration of patient images obtained at different times. Kirbas et al. list in [9] no less than ten medical application fields from the extraction of neurovascular structures to the segmentation of nerve channels, from several medical specialities (cardiology, obstetrics, gynaecology, and so on)[1].

One of the most promising applications of medical image computerized visualization is virtual reality surgical planning [13], avoiding the traditional difficult mental 3D model creation by a surgeon from a stack of intensity-based images, usually from computerized tomography (CT) scanners. By using volumetric renderings of anatomical structures, and the appropriate virtual tools for basic surgical operations, the complexity of many plastic surgery interventions can be addressed ahead of the actual physical procedure. However, the main bottleneck for these computer environments is the delineation of the tissues involved, to such an extent that automated approaches become necessary.

Image segmentation refers to the extraction of the target object boundaries from a single image or a set of images. The segmentation of such images involves obtaining an accurate depiction of interesting tissues or organs with constraints on user intervention and processing times [15]. Segmentation methods vary, depending on the imaging modality (Magnetic Resonance Angiography (MRA), Computerized Tomography Angiography (CTA), 3D Rotational Angiography (3DRA), Ultrasound+Doppler imaging, etc.) or application domain: there is no single segmentation method that can extract vasculature from every medical image modality. Moreover, depending on the image quality and the general image artefacts such as noise, some segmentation methods may require image pre-processing prior to the segmentation algorithm, and also possible post-processing to overcome the problems arising from over segmentation [9]. Blood vessel segmentation has been an early been a focus of interest; in 1995, Archaya et al. [1] detailed then existing segmentation techniques. Although continuing improvements in computer technology have significantly reduced the need for user intervention, image segmentation in medical applications is still the result of a good balance between automation and user interaction. This is why modern segmentation methodologies aim at automation, accuracy, reproducibility, and efficiency, still allowing for necessary intervention by the user, who tunes the results of the segmentation process or interacts to make corrections on the current status [15].

Today, blood vessel segmentation is still a challenge. Hao et al. describe in [7] some factors depicting the difficulties: in essence, blood vessels are elongated structures whose widths vary largely from great arteries to blood capillary; second, TOF MRA[2] imaging makes the gray-scale range of blood vessels wide. Furthermore, noise and artefacts exert additional difficulties on the segmentation.

Popular vascular segmentation methods are based on several techniques, which can be classified according to a rich taxonomy provided by [9] featuring seven families and a few subcategories of segmentation techniques from pattern recognition to neural networks. More popular approaches belong to the model based (in this case, segmentation is considered as a registration problem by mapping or deforming the image onto a pre-segmented reference image or template) and gradient based (with active contours or level set methods, for instance) methods. Radaelli et al. provide a detailed survey on these classical techniques in [15].

Three other advanced segmentation techniques can also be considered:

- The Right Generalized Cylinder (RGC) state model based technique, proposed by Flórez Valencia et al. in [5], reconstructs from CTA images, the RGC shape step-by-step, by extracting consecutive cross-sectional contours along an approximate vessel axis. The continuity and smoothness are controlled by a Kalman state estimator, which predicts the 3D locations, orientations and shapes of the contours that delimit the consecutive cylinder pieces. The contour extraction uses the Fast Marching method
- The Multi-Attribute Fuzzy Clustering Algorithm [7] works on TOF MRA images and takes both the intensity information and the geometric information into account while most of the current clustering methods only deal with the former. Because of the presence of geometric information, the new measure allows differentiating pixels with similar intensity values within different geometric shape structures.
- The Tubular Structure Segmentation Based on Minimal Path Method and Anisotropic Enhancement [3] is an interactive method, which exploits the orientation of the vessels from 2D or 3D images by using the optimally

---

[1] Some general references and others specific to medical domains are provided in [15].

[2] TOF (Time of Flight) if a fast MRA providing high contrast images, where flowing blood itself is used as a contrast agent [7, 15].

oriented flux to construct a multi-resolution anisotropic metric that extracts from the image the local geometry and describes the vessels orientation and scales. Combining this metric with the anisotropic minimal path technique, authors were able to find a complete description of the tubular structure, i.e., the centerline as well as the boundary.

Further enhancements in segmentation techniques should aim at eliminating user intervention and thus subjective and supervised evaluation, i.e., the 'psychological perception' element in segmentation. Improvements in image quality through advancement in acquisition technology will also help considerably in reducing measurement uncertainty in a clinical environment, but are unlikely to eliminate it completely [15].

3. OVERVIEW OF OUR APPROACH

In order to support accurate and safe navigation of the surgical tools inside a patient, the capability of visualizing the navigation path in 3D space is crucial. There are three main approaches for segmentation of 3D objects. The first one is manual tracing in which a human operator delineates each 2D slice in a volume. This method is time consuming and not feasible when the volume data is large. Also, this method may not produce identical results when different operators perform the same task. The second approach is fully-automated segmentation in which no human intervention is required. However, this approach suffers from sensitivity to parameterization and variation of biological structures among different subjects. Researchers have recently become interested in semi-automated methods in which computer-based segmentation is facilitated by minimal human interaction.

Our approach consists of the following steps:

1. Specifying Livewires in two orthogonal directions for a given CT slice.

2. Determining Livewire in the third orthogonal direction.

3. Performing segmentation using the initial Livewire seeds for other CT slices.

4. Performing Skeletonization of the segmented blood vessels to suggest a navigation path during surgery.

Outline of Skeletonization Technique

Our technique, inspired by the Sphere Sampling approach [20], uses overlapping maximal spheres to cover the free space inside the 3D object. The following steps are applied:

1. Starting from a user-defined face on the surface, compute its normal and project the reverse normal inside the object on the opposite surface.

2. Fit a maximal sphere along the path inside the object. Record the sphere center as a skeleton point.

3. A fixed number of sample points (children) are placed evenly on the circumference starting from a predefined orientation, based on a user-defined separation angle θ [19]. For each child, a maximal sphere is drawn. If the sphere touches at least two vertices on the surface, the child becomes a skeleton point and is linked to the center of the parent sphere. Also, a sphere is valid only if its radius is larger than a predefined threshold R.

4. The valid spheres are pushed into a priority queue in descending radius order.

5. A sphere is popped from the queue and Steps (3) to (5) are repeated until the queue is empty.

Figure 1 (a) to (d) shows the skeletons of a horse, a cow, a dragon and a bunny models respectively. Different colors are used for easy visualization of the parent-child hierarchy.

Many significant features are built into our algorithm in order to generate a stable skeleton:

a) The mid-point of two children with equal and opposite vectors perpendicular to the surfaces is not taken as a skeleton point in [20] causing valid points missing from the final skeleton. The mid-point is a skeleton point in our approach.

b) The original sphere sampling approach starts with a random point inside the object as the center of a sphere with radius larger than a predefined threshold. Another random point is selected if the sphere cannot fit inside the object. The skeleton stability is not guaranteed due to the random selection. We start from a user-defined location and project the face normal to the opposite surface of the object. If the diameter of a sphere can fit into the space in between, the sphere is valid, otherwise the sphere is adjusted adaptively to fit into that location, so that a stable skeleton can be generated.

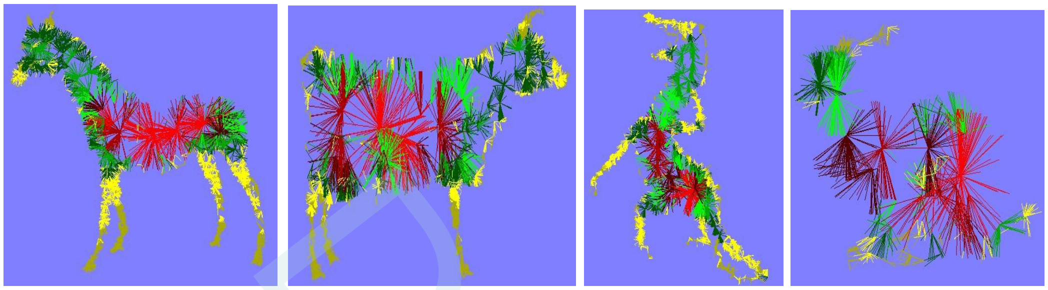
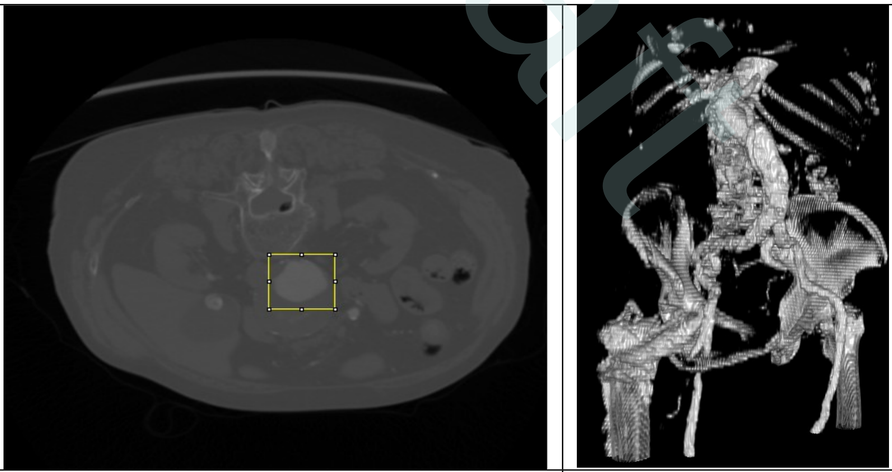


Figure 1: *Skeleton: (a) horse, (b) cow, (c) dragon and (d) bunny. Different colors are used on the skeleton for easy visualization of the parent-child hierarchy.*

4. Experimental Results



(a) A sample CT slice in axial view. The aorta is inside the rectangle.

(b) 3D view of the CT after applying intensity windowing.

Figure 2: (a) Sample CT slice and (b) results from OSIRIX.

Since the intensities of arteries are near the intensities of the bone structures in the dye-enhanced CT series, simple windowing techniques are not sufficient for segmenting arteries (Fig. 2). The target region has to be scanned at the time when the dye has emerged in order to obtain good contrast images. We used a semi-automatic 3D segmentation environment using 3D livewires [14]. The manual part is performing 2D Livewire segmentations on slices in any two orthogonal orientations. The seedpoints of the Livewire in the third orthogonal orientation is determined by these 2D contours. The Livewires in three directions form a ‘seedpoint map’ which is used to perform automatic 2D Livewire segmentation in other slices. Figure 3 (left) illustrates the 3D segmented artery using this method. The accuracy of the segmented 3D arteries is verified by clinical surgeons. Results of robust 3D medial axes extraction of blood vessels can be seen in Figure 3 (right).

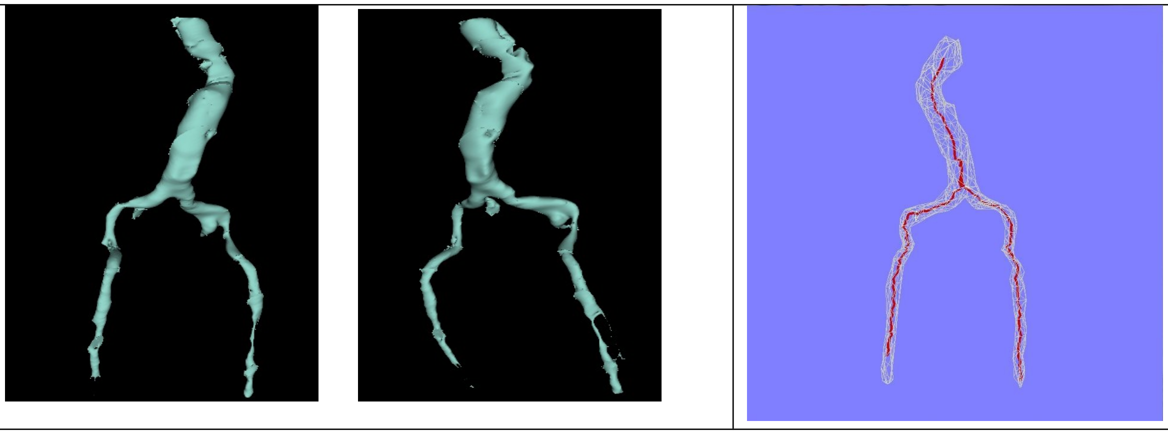


Figure 3: (Left) result of 3D segmentation using initialization of livewires followed by Turtleseg; (Right) medial axis extracted by our skeletonization algorithm.

5. CONCLUSION AND FUTURE WORK

Accurate segmentation of the artery and generation of the medial axes is a fundamental step in planning, tracking and correcting the optimal path for navigation of surgical tools. Improving the automatic planning process during endovascular surgery has many important implications as explained earlier. We have completed initial studies on improved segmentation and medial axes extraction. In future work we will focus on automatic planning and guidance of a surgical end-effector.

Acknowledgements

The authors thank Alberta Innovates (Alberta), NSERC (Canada) and AANR (France) for financial support in this research. Note that our work on skeletonization was presented in a student poster session earlier.

References

[1] Acharya, R., Wasserman, R., Stevens, J. and Hinojosa, C., “Biomedical imaging modalities: a tutorial,” Computerized Medical Imaging and Graphics, 19, 3 – 25 (1995).
[2] Antoniou, G.A., Riga, C.V., Mayer, E.K., Cheshire, N.J., and Bicknell, C.CD., “Clinical applications of robotic technology in vascular and endovascular surgery,” J. vascular surgery, Feb 2011, vol. 53, no. 2, 493-499 (2011).
[3] Benmansour, F. and Cohen, L., “Tubular Structure Segmentation Based on Minimal Path Method and Anisotropic Enhancement,” J. Computer Vision, Springer Netherlands, *92*, 192-210 (2011).
[4] Bailly, Y. and Amirat, Y., “Modeling and Control of a Hybrid Continuum Active Catheter for Aortic Aneurysm Treatment,” Proc. IEEE Int. Conf. Robotics and Automation, Barcelona, Spain, 924-929 (2005).
[5] Flórez Valencia, L., Azencot, J., Orkisz, M., Bolc, L., Tadeusiewicz, R., Chmielewski, L. and Wojciechowski, K. *(Eds.)*, “Algorithm for Blood-Vessel Segmentation in 3D Images Based on a Right Generalized Cylinder Model: Application to Carotid Arteries,” Computer Vision and Graphics, Springer Berlin / Heidelberg, 6374, 27-34 (2010**).**
[6] Guo, S., Kondo, H., Wang, J., Guo, J., Tamiya, T., “A New Catheter Operating System for Medical Applications,” Proc. IEEE Int. Conf. Complex Medical Engineering, Beijing, China, 82-86 (2007).

[7] Hao, J., Zhao, J. and Li, M., “Spatial continuity incorporated multi-attribute fuzzy clustering algorithm for blood vessels segmentation,” SCIENCE CHINA Information Sciences, Science China Press, co-published with Springer, 53, 752-759 (2010).
[8] Kesner, S.B., and Howe, R.D., “Force Control of Flexible Catheter Robots for Beating Heart Surgery,” Proc. IEEE Int. Conf. Robotics and Automation, Shanghai, China, 1589-1594 (2011).
[9] Kirbas, C. and Quek, F., “A review of vessel extraction techniques and algorithms,” ACM Comput. Surv., 36, 81-121 (2004).
[10] Klein, L.W., Miller, D.L., Goldstein, J., Haines, D., Balter S., Fairobent, L. and Norbash, A., “The catheterization laboratory and interventional vascular suite of the future: Anticipating innovations in design and function,” Catheter Cardiovasc Interv., 77, 447-455 (2011).
[11] Mahvash, M. and Dupont, P., “Stiffness Control of Surgical Manipulators,” IEEE Trans. Robotics, 27:2, 334-345 (2011).
[12] Mangnan, V., Kingsley, D., Quinn, R., and Chiel, H., “Development of a peristaltic endoscope,” Proc. IEEE Int. Conf. Robotics and Automation, Washington, USA, 347–352 (2002).
[13] Mendoza, C., Acha, B., Serrano, C. and Gómez-Cía, T., “Fast parameter-free region growing segmentation with application to surgical planning,” Machine Vision and Applications, Springer Berlin / Heidelberg, Issn: 0932-8092, 1-13 (2010).
[14] Poon, M., Hamarneh, G. and Abugharbieh, R., “Efficient Interactive 3D Livewire Segmentation of Objects with Arbitrarily Topologies,” Computerized Medical Imaging and Graphics, 32, 639-650 (2008).
[15] Radaelli , A.G. and Peiró, J., “On the segmentation of vascular geometries from medical images,” Int. J. Numerical Methods in Biomedical Engineering, John Wiley & Sons, Ltd., 26, 3-34 (2010).
[16] De Sars, V., Haliyo, S., and Szewczyk, J., “A practical approach to the design and control of active endoscopes,” Mechatronics, 20:2, 251-264 (2009).
[17] Simi, M., Sardi, G., Valdastri, P., Menciassi, A., and Dario, P., “Magnetic Levitation Camera Robot for Endoscopic Surgery,” Proc. IEEE Int. Conf. Robotics and Automation, Shanghai, China, 5279-5284 (2011).
[18] Zhang, B., Kobayashi, Y., Maeda Y., Chiba, T. and Fujie, M.G., “Development of 6-DOF wire-driven robotic manipulator for minimally invasive fetal surgery,” Proc. IEEE Int. Conf. Robotics and Automation, Shanghai, China, 2892-2897 (2011).
[19] M. Foskey, M. Lin and D. Manocha, “Efficient Computation of a Simplified Medial Axis,” In *Proc. of the 8th ACM Symposium on Solid Modeling and Applications*, pp 96-107, 2003.
[20] Y. Yang, O. Brock and R. Moll, “Efficient and Robust Computation of an Approximated Medial Axis,” In *Proc. of the ACM Symposium on Solid Modeling and Applications*, pp.15-24, June 2004.