Automatic generation of real-time deformable parametric model of the aorta for a VR-based catheterism guidance system

P. Fontanilla Arranz[1], B. Rodríguez Vila[1], A. Dore[2], M. Sette[3], P. Sánchez-González[1], J. Vander Sloten[3], E.J. Gómez Aguilera[1]
[1]ETSI de Telecomunicación, Universidad Politécnica de Madrid, Bioengineering and Telemedicine Centre, Madrid, Spain
[2]Imperial College London, The Hamlyn Centre for Robotic Surgery, London, United Kingdom
[3]Katholieke Universiteit Leuven, Robot-Assisted Surgery Group, Heverlee, Belgium

Keywords: catheterism, non-rigid registration, parametric model, guidance system

Purpose

The purpose of this work is twofold: first, to develop a process to automatically create parametric models of the aorta that can adapt to any possible intraoperative deformation of the vessel. Second, it intends to provide the tools needed to perform this deformation in real time, by means of a non-rigid registration method. This dynamically deformable model will later be used in a VR-based surgery guidance system for aortic catheterism procedures, showing the vessel changes in real time.

Methods

Automatic generation of the preoperative parametric model

The aorta model used for development is based on a computer graphics technique, skeletal animation [1], and is composed of two parts: a polygonal surface, or skin, and a centerline approximated by straight segments (bones), known as skeleton, Fig. 1.

The surface is extracted from a preoperative magnetic resonance image. In this research work, a silicone phantom has been used. The preoperative image is segmented with ITK-Snap and reconstructed using the marching cubes algorithm. The skeleton is calculated afterwards, as a hierarchical chain of bones [2]. The algorithm uses two parameters: maximum deviation of the skeleton from the centerline (D), which controls the accuracy of the straight segment approximation, and maximum bone length (L), which affects the skeleton's rigidity.

These two pieces, surface and skeleton, are then joined in a process called skinning, that will assign each vertex of the polygonal surface to a bone, using a modified and weighted minimum distance criteria [3].

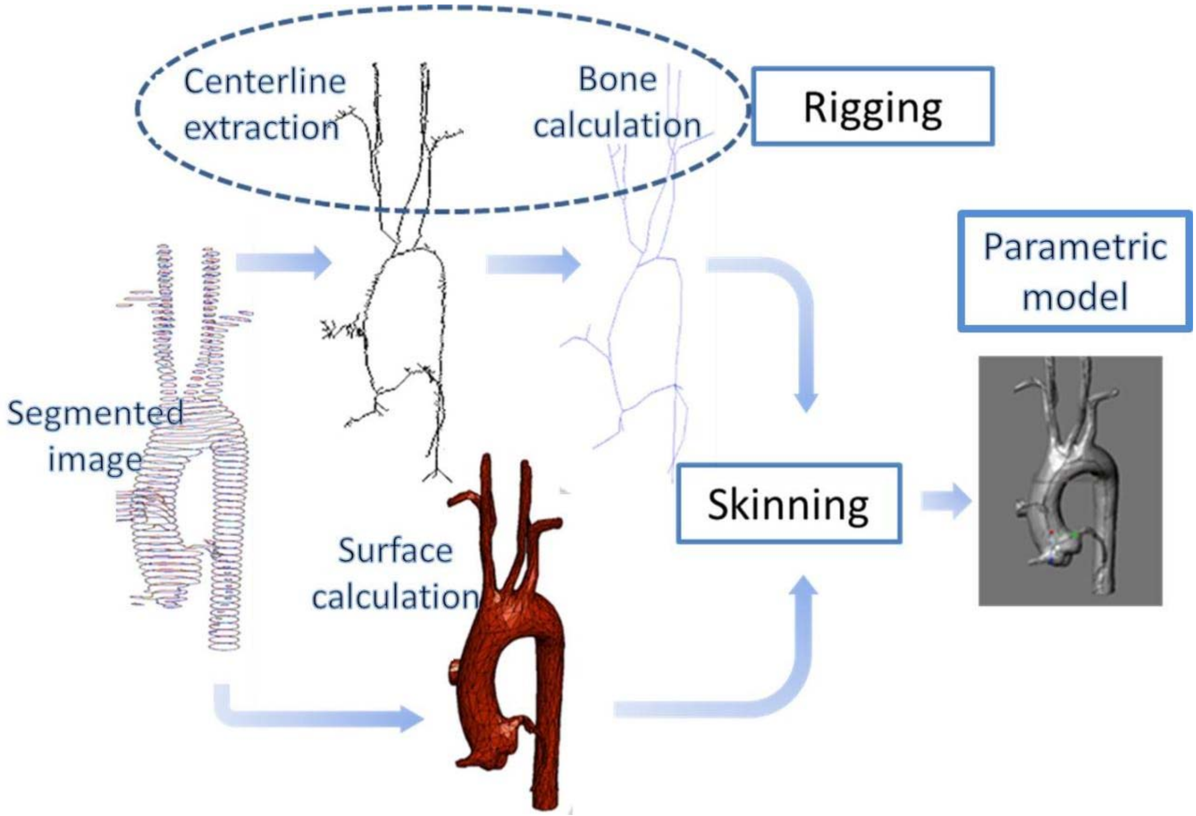

Fig. 1. Creation of the parametric model, including the skinning and rigging process

Real-time non-rigid registration to the intraoperative information

The proposed registration method is focused on modelling the longitudinal deformations of the vessel, not the pulsatile ones. So, the method is based on adapting the preoperative skeleton to the intraoperative information, offering the surgeon a model of the aorta, and catheter position and shape, updated in real time.

Our goal is to find the bone positions of the model's skeleton that best match the current vessel centerline, update them and adjust the surface to this new skeleton. The method is twice iterative: the skeleton configuration is computed in a bone-by-bone fashion (main loop), and the optimal position of each bone is also computed iteratively (bone loop).

In the main loop, the current vessel centerline data is calculated from information provided by two devices installed on the catheter: intravascular ultra sound (IVUS) images from a probe on the catheter tip, and an electromagnetic tracking system (Aurora), which offers an estimated curve of the catheter shape inside the vessel. Thus, the intraoperative centerline of the aorta is computed. The second step of the main loop is composed of an initial sub step and the bone loop. In the initial sub step, the starting bone is selected, choosing the closest bone of the skeleton to the catheter tip in the Z direction. This bone is translated in the XY plane so the catheter tip point is included in the bone segment. The initial end of the bone is fixed, and the method then searches for the optimal position of the final end in the bone loop.

The bone loop is initialized by obtaining an approximate angle for the bone, and then the optimal value of this angle is computed iteratively to minimize the approximation error (Figure 2). To find a first approximation of this angle, we sequentially advance the final end of the bone through the centerline curve and measure its distance to the initial end. Once the distance between the initial end and the final end is greater than the bone length (fixed in the skeleton creation), the sequence is stopped. The angle set by this last position is accepted as a preliminary result and used as basis for the next sub-step.

The next sub-step considers a sphere with radius equal to the bone length and centered in the initial end of the bone. Points belonging to the sphere and within a distance of the previous approximation point are tested as possible positions for the bone end. For each one, its bone error is calculated and a final best end point is chosen. The number of points used can be as large as the computational time and needed refresh rate permits.

These two sub-steps will be performed for each bone, using the last bone's final end as the next bone's initial end, until all of the bones, and therefore the whole centerline has been fitted. This fitting will take place each time the intraoperative information is updated, or after a certain timeout.

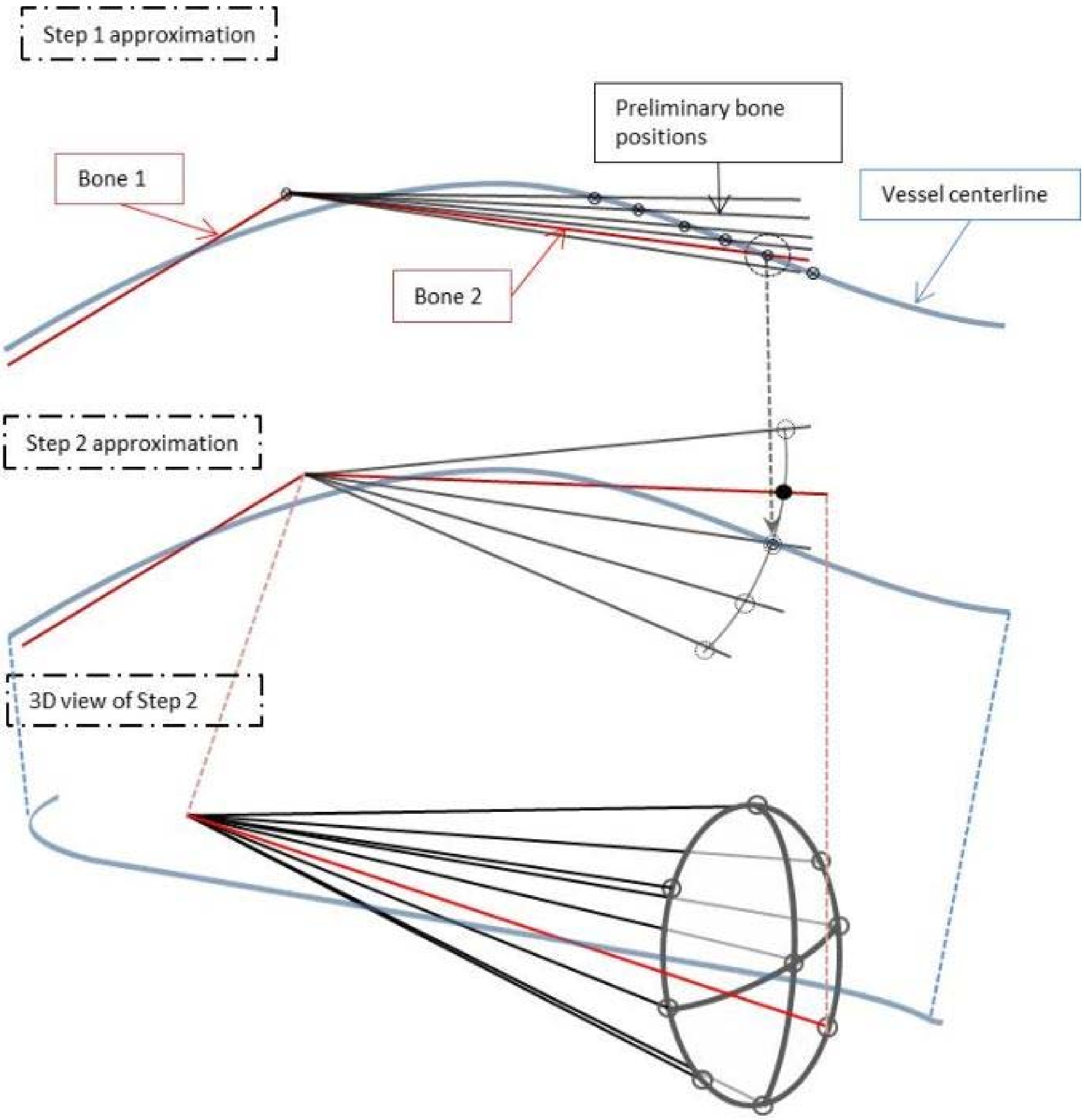

Fig. 2. Approximation steps carried for each bone: (top) initial angle approximation, (middle) fine tuning phase shown in 2D, (bottom) fine tuning shown in 3D

Results

Validation of the results has been performed in different experiments, and the results suggest that a maximum bone length L = 10 mm and a maximum deviation from the centerline D = 2mm create correct and realistic configurations. This takes less than 10 seconds in a dual core, 4 GB RAM, 64 bit OS desktop computer.

The quality of the model is proportional to the quality of its skeleton, which depends on the number of bones used to approximate the centerline. An excessive bone length (L) produces large bones and results in rigid skeletons. Likewise, an excessive centerline deviation (D) downgrades the quality of the approximation, and may lead to erroneous vertex-bone assignments.

The registration algorithm is in validation status, but the preliminary results show that our first implementation is fast enough in the aforementioned computer to provide up to date results for the guidance system.

Conclusions

An automatic method of creation of deformable parametric models for use in real-time aortic catheterism guidance has been presented. The generated models are composed of a polygonal mesh and an articulated rigid skeleton, both obtained automatically from preoperative segmented MR images of the aorta. Moreover, a non-rigid method has been proposed, providing real-time adaptation of the parametric models to the intraoperative information. This greatly enhances aortic catheterism guidance systems, providing a way to show updated information on the vessel and catheter status during the procedure.

References

[1] Lever N. “Real-time 3D Character Animation with Visual C++”. (2002) Focal Press, ISBN: 0240516648

[2] Siddiqi K, Bouix S, Tannenbaum A, Zucker SW, (2002) Hamilton-Jacobi skeletons. International Journal of Computer Vision 48 (3), 215-231

[3] García-Peces FJ, Rodriguez-Vila B, Sánchez-González,P Gómez Aguilera, E.J. Anatomical model parameterization of the aorta for Real-Time VR Environment , Proceedings for the I Joint Workshop on New Technologies for Computer/Robot Assisted Surgery, Graz 2011