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VR simulated training for less invasive vascular intervention

Yiyu Cai[a,*], Cheekong Chui[b,e], Xiuzi Ye[c,f], Yaoping Wang[b], James H. Anderson[d]

[a] *School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Nanyang 639798, Singapore*
[b] *Bio-medical Imaging Lab, Kent Ridge Digital Labs, 13 Hong Mui Keng Terrace, Singapore*
[c] *College of Computer Science and Engineering/State Key Lab of CAD and Computer Graphics, Zhejiang University, People's Republic of China*
[d] *School of Medicine, Johns Hopkins University, Baltimore, MD, USA*
[e] *Graduate School of Frontier Science, University of Tokyo, Japan*
[f] *Solidworks Corp., Massachusetts, USA*

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Abstract

This paper describes a computerized simulation system for less invasive vascular interventions using virtual-reality (VR)-based technology. A virtual human patient is constructed on top of the visible human data (VHD) incorporating in various vascular disease cases. Specially, the human vascular network is modeled for the use of catheterization simulation. Physical modeling technique is applied to model the interaction between the blood vessels and vascular catheterization devices. A haptic interface is integrated with the computer simulation system to provide tactile sensations to the user during the simulated catheterization procedures. The system can be used for training and pre-treatment planning of interventional vascular procedures.

Keywords: Virtual reality; Simulation; Less invasive vascular intervention; Geometric modeling; Haptics

1. Introduction

1.1. Virtual reality and its applications

As an emerging technology, virtual reality (VR) is getting increasingly popular in both academia and industries. It is evolving from VR to augmented reality (AR) and merging into mixed reality (MR) [1]. While fundamental VR research such as new algorithms and new methodologies [2–4] are rapidly emerging, VR has found great applications [5] in science, medicine, architecture, manufacturing, design, education, entertainment, etc. We are interested in applying VR technology for the training of less invasive vascular intervention.

1.2. Training of vascular intervention

Interventional radiological procedures are often used in place of surgery to minimize the invasiveness, patient discomfort, and general anesthesia associated with surgery and to reduce the cost and length of hospitalization.

In performing such procedures, interventionists must be very careful to avoid injury to the patient when manipulating of interventional devices within the blood vessels. Examples of injuries include rupturing or dissecting the wall of the vessels. To reduce these complications, medical students or junior interventionists require long and intensive training which usually starts from watching and assisting the experienced and certified interventionists in performing actual clinical cases. There is a need to provide additional means to train students or junior interventionists in order to improve their necessary skill levels. A realistic and computerized simulation system [6] could complement and enhance the traditional type of training with real

*Corresponding author. Tel.: +65-67905777; fax: +65-679-11859.
E-mail address: myycai@ntu.edu.sg (Y. Cai).

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patients. Several interventional radiology simulation systems have been reported in the literature. Anderson et al. [7] presented their catheterization simulator called *daVinci* at the 21st SCVIR annual meeting in 1996. Dawson and Kaufman with HT Medical, Inc. [8,9,10], developed their interventional radiology simulator for angioplasty and other techniques. Wang et al. [11] developed a simulator for training of percutaneous coronary revascularization procedures. Other researches on simulation of interventional catheterization or less invasive therapy have also been published in [12–14].

1.3. Briefing of this paper

This paper discusses the development of a VR-enhanced simulator for vascular interventional training. In the following sections, a virtual and variational patient is first presented. This virtual patient is characterized by its capability of the variational change of the typical vascular diseases. A novel approach to modeling the human vascular networks is then described. The approach offers improved efficiency for vascular model display and interventional device manipulation. This is followed by the discussion of an efficient potential field method for the physically based modeling of the interaction between interventional devices and vascular walls. Finally, a haptic device to facilitate tactile sensations in the manipulations of catheterization devices is presented.

2. Virtual and variational vascular patient

In order to build a high fidelity simulator for training of vascular interventions, a computerized virtual patient model is necessary. Individual patients may demonstrate different vascular diseases, different diseased sites, different levels of diseased lesions and so on. Virtually, every vascular patient can be a training case and the vascular patient database, therefore, should include a large pool of real patient records covering enough diseased cases. This, however, may potentially lead to data crunching and computationally intensive problem in terms of data management.

2.1. Virtual vascular patient

We propose here to design a virtual patient with a variational feature to represent many typical vascular diseases. In other words, this virtual patient can be configured with several common vascular diseases such as coronary vascular lesions, carotid bifurcation stenosis, or abdominal aortic aneurysms (AAA) (Fig. 1). For instances, percutaneous transluminal coronary angioplasty (PTCA) training can be simulated with the virtual patient whose vascular model has one or more coronary stenosis.

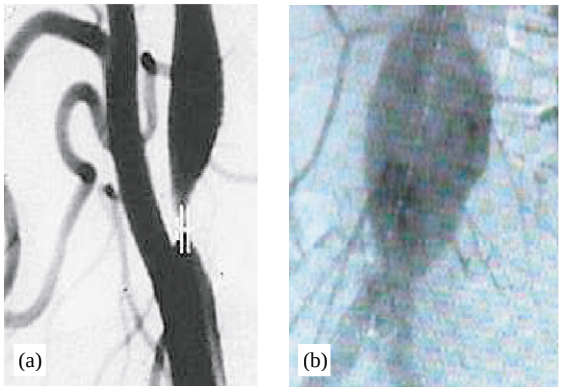

Fig. 1. Vascular diseases: (a) carotid stenosis and (b) AAA disease.

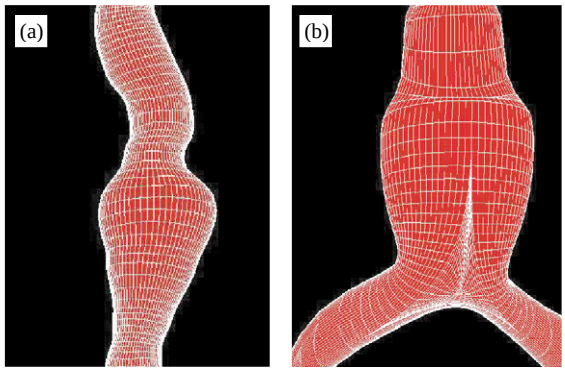

Fig. 2. Synthesized vascular diseases: (a) synthesized stenosis and (b) synthesized AAA.

2.2. Parameterization of vascular diseases

To create different models of diseased vessels, we first classify various vascular diseases into several typical cases. Salient features associated with those typical cases such as lesion site, type, length, diameter, etc., are then identified. Vascular anatomic variants can be incorporated in this feature identification process. Since the disease database is parametric based, variations of the vascular diseased cases can be computationally modeled. Theoretically, an unlimited number of diseased cases can be synthesized if methods such as Monte Carlo random case generation are applied. One of the advantages of this variational-based disease modeling is that blind testing for diagnosis and then treatment can be simulated for the training purposes. Fig. 2 illustrates the synthesized vascular diseases. Detail description of human vascular network modeling will be given in Section 3.

We use the VHD as a default virtual patient. Fig. 3 shows the volume rendered VHD virtual patient. A customized vascular network can be modeled on top of the default VHD data with specific diseased

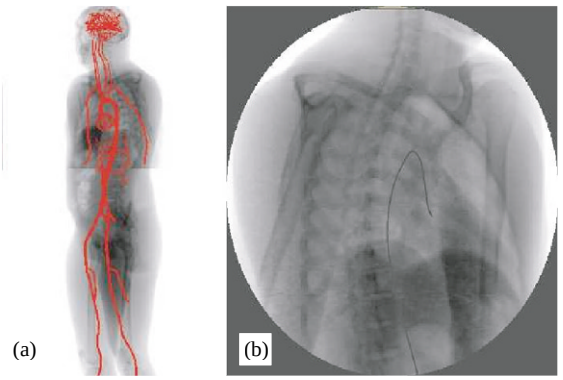

Fig. 3. A Virtual and variational patient: (a) volume rendered fluroscopic views of the virtual patient with the vasculature demonstrated; and (b) shutter and scaled view of the virtual patient.

information. Manipulations of the virtual patients including zooming, rotation and translation, cine shuttering, etc., have been developed. These operations are designed to simulate the type of fluoroscopic images normally encountered in the interventional radiology treatment suite.

3. Localized vascular modeling

Interventional radiology deals mainly with human vascular systems. Modeling of the vascular network is therefore a critical step in developing interventional simulators. In [7], the iso-surfacing technique was applied to generate the vascular surfaces. With such vascular wall surface model, simulated passage within the blood vessels becomes feasible. Typically, the extracted vascular iso-surface model is made of tessellated triangular meshes. Neighboring or adjacent relationship among triangles are usually not explicitly expressed. Updating of the vascular model, even with very small modifications at a local region will have to involve a complete regeneration of the vascular iso-surfaces. This poses difficulty for real-time operations including graphical rendering with the vascular wall surfaces. Often high-end graphic workstations like Onyx2 are required to levitate the computational and rendering load of huge amount of triangle nets.

3.1. Vascular segment modeling

We have developed a novel approach to modeling vascular networks [15]. A basic divide-and-conquer strategy is applied here to separate the vascular segments at various joints. This allows localized modeling of the vascular system. A central line model of the vascular networks is used to serve as a topology graph. Based on the central lines, it is relatively easy now to reconstruct the vascular segments using a sweeping technique.

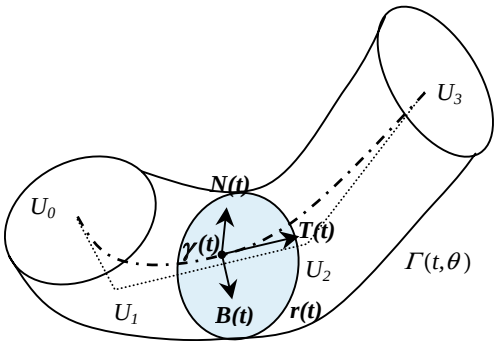

Fig. 4. Tube segment sweeping.

Let $\gamma(t)$ be any of path in cubic Bezier form, a local coordinate Frenet frame $(T(t), N(t), B(t))$ can be defined along the path. Assume $r(t)$ is a contour function, not necessary circular, defined in the cross-sectional plane perpendicular to the curve at a given point along the trajectory. The sweeping surface (Fig. 4) can be represented by

$$\Gamma(t,\theta) = \gamma(t) + r(t)(\cos\theta\, N(t) + \sin\theta\, B(t)),$$

where θ is the cross-sectional angle and $t \in [0,1]$ is a parameter defined along the path.

3.2. Vascular bifurcation modeling

Modeling of the joint or bifurcation is more difficult. Sweeping and hole filling techniques are used here to create bifurcation model. Principally, for each joint, three half tubular surfaces are swept, similar to segment modeling, to form an initial bifurcation. The triangular hole filling technique [16] is then applied to form a complete bifurcation. Constructive modification technique is developed for G^1 or tangential smooth representation of the joint surfaces by considering the cross-boundary tangential continuity, twist-compatibility and unique existence of tangent planes at triangular hole corners. The procedure can be summarized as follows (Fig. 5):

(i) Three half-tubular surfaces in bi-cubic Bézier form are generated using sweeping operations (red, green and blue).
(ii) Two triangular holes (purple) are formed by three surrounding half-tubular surfaces. Each hole is initially "filled" with three bi-cubic Bézier patches.
(iii) The boundaries of the half-tubular surfaces are modified to quintic form to allow cross-boundary tangential continuity, twist-compatibility and unique existence of tangent planes at hole corners.
(iv) Three half-tubular surfaces are then degree-elevated into quintic Bézier patches and modified based on the new hole boundaries. The next row of the control points of the hole boundaries are

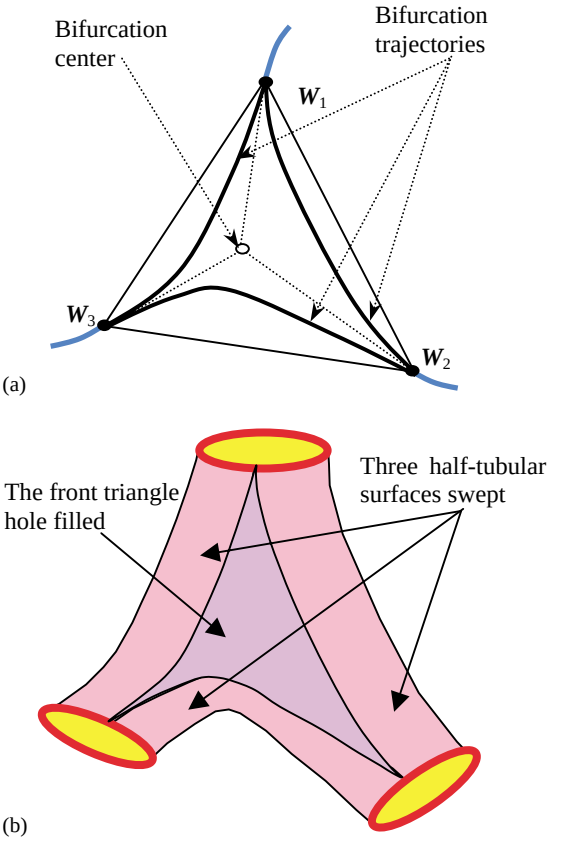

Fig. 5. (a) Bifurcation trajectory construction; and (b) bifurcation modeling with tangential continuity.

modified accordingly to ensure the half-tubular surfaces having cubic cross-boundary derivatives along the hole boundaries.

(v) The vector-valued cross-boundary derivative in a quintic form along the hole boundaries are generated for the filling hole patches.

(vi) The hole boundaries are split into two at the middle point of parameter, so are the associated vector-valued cross-boundary derivatives. The star-lines and their associated vector-valued cross-boundary derivatives are degree-elevated to quintic as well.

(vii) Three final filling rectangular patches are generated based on the updated star-lines, split hole boundaries, and the vector-valued cross-boundary derivatives along the star-lines and the split hole boundaries. The remaining 3×3 interior control points are determined by taking the Coons-Boolean sum approach.

The vascular modeling approach developed makes surface tessellation (triangular or quadrilateral) extremely simple. This is because vascular tubular segments are modeled by sweeping and hole filling operations that produce regular rectangular topology with all the surface patches in the parameters domain. Tessellation on the rectangular grids for generalized sweeping tubes is straightforward. For bifurcations, this can be similarly done with the three half-tubes swept and two triangle holes filled.

If the vascular networks are modeled from vascular central lines piece-by-piece, the tessellated vascular surfaces can easily organized in a similar order together with all the vascular joints. Level of detail technique can then be developed to represent the vascular network. Thus, if a segmental tube is identified, its corresponding central line can be determined and vice versa. At the joints, however, all the connected branches should be determined. This allows local operations within selected vascular segments. For instances, when vascular walls are deformed due to a catheter tip interacting with the vessel wall, only relevant triangular meshes near the contact region need to participate in the finite element analysis (FEA). In other words, a majority of non-neighboring segments can be waived from the time-consuming computation. Therefore, only very few triangles should be modified and graphically updated.

4. Efficient physical modeling for catheter navigation

4.1. Physical modeling for catheter navigation

In catheterization procedures, interventional devices will interact with the vascular walls when the devices are manipulated with movements of forward, backward, twisting, inflation, deflation, etc. Realistic simulation of catheter intervention must properly address these phenomena. Our simulation involves in the physical behaviors of both interventional devices and vascular walls. As described in [17], a potential field method was developed to support the physically based modeling for vessel-device interaction. To handle the FEM-based numerical calculation of the interaction, a discrete potential field (Fig. 6(a)) is generated that is typically represented by multi-dimensional cloud data at the grid points surrounding vascular walls.

When a FEM-meshed node at the interventional device interacts with the vascular wall, the potential fields for the accurate node is tri-linearly interpolated and used to speed up the computing of the deformation force as well as the displacement, typically in an iterative manner [17]. When the whole human vascular networks are used for interventional simulation, the cloud data surrounding with the vascular tree can be extremely huge that can cause problems for data saving and calculation as well.

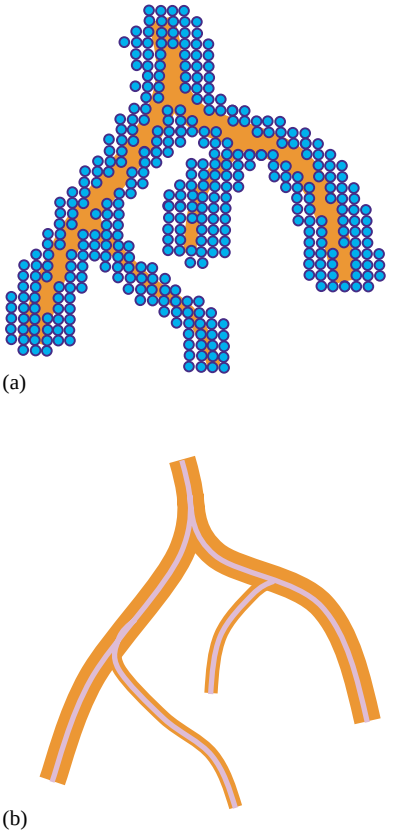

Fig. 6. Potential field supported physical modeling: (a) Discrete potential field and (b) central topology based potential field.

4.2. Continuous potential field

To solve this problem, instead of using a discrete mode, a continuous potential field is introduced that uses direct calculation for a FEM node. This, however, requires a query of the corresponding vascular segment given the current FEM node. Usually, such a query can be very expensive. We first represent the network in a hierarchical structure. When the FEM nodes are moving along a segment, the topology tree is tracked and updated when the nodes are across the vascular joints. The topological adjacency helps to reduce the searching and therefore make the potential field calculation very efficient.

5. Haptic VR-enhanced training

VR technology is applied in this project to develop an interventional simulation environment. For less invasive vascular interventional training, hand–eye coordination is utmost important in order for trainees to gain a realistic experience in catheterization procedures. For this purpose, a haptic interface is designed. The prototype of the haptic interface consists of an electro-mechanical unit, a digital balloon inflation unit and several others.

5.1. Catheter motion tracking and ballooning

The electro-mechanical unit is for tracking of the movements of real catheterization devices inserted in an apparatus that can be embedded in a mannequin. The motion tracking is realized using a track-ball based technique. Force-feedback is also incorporated with the apparatus to synthesize the resistance when navigating of the catheterization devices. Fig. 7 is an overview of the electro-mechanical unit for interventional training. A digital inflation unit is designed for trainees to simulate the balloon inflating and stenting. Fig. 8 shows the prototype of the unit.

5.2. VR-enhanced training for vascular intervention

With this haptic device, several interventional procedures can be simulated. The trainee can insert actual

Fig. 7. The electro-mechanical unit for catheter/guide-wire insertion and contrast die injection.

Fig. 8. The digital balloon inflation unit.

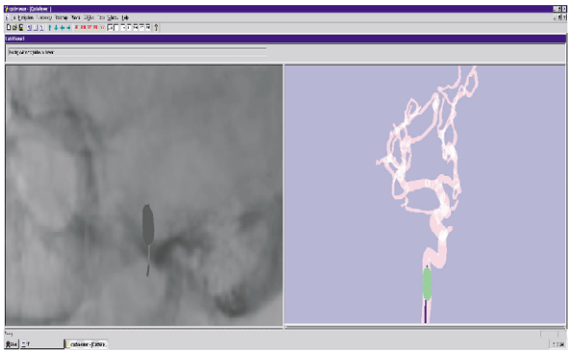

Fig. 9. Simulation of balloon inflation.

Fig. 10. Simulation of stent deployment with balloon inflation.

catheters and guide-wires into the virtual patient who can be configured with certain types of vascular diseases. The trainee can use this training device to simulate the diagnose procedures with the various aids of fluoroscopic imaging and die contrast injection, etc. The trainee can also use the balloon inflation device to simulate therapy procedures such as PTCA. Figs. 9 and 10 illustrate the simulation of ballooning and stenting using the haptic device.

The VR interventional simulator enhances the hand–eye coordination for catheterization training. The VR-based training environment integrates physically based vascular modeling and haptic interventional interfacing. A calibration of real and virtual catheterization devices is conducted to improve the accuracy of human–machine interaction within the environment. The whole environment is implemented on a PC Window/NT platform using OpenGL and visual C++ programming.

6. Conclusion

This work presents a computerized simulator for less invasive vascular interventional procedures using VR technology. A virtual simulation environment is developed incorporating major components of virtual and variational patient, physically based and geometrically based vascular modeling, and haptic interventional interfaces. With the virtual haptic training environment, hand–eye coordination, necessary for interventional radiology can be enhanced. The work is targeting at low-cost PC desktop platform applications.

As a desktop VR application, less immersion feeling is available with the system. This is in line with the interventional practice and the interventional training emphasizes very much on hand–eye coordination instead of immersion. Future works includes simulating blood flow and multiple image modalities presentations.

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