Proceedings of the 2017 IEEE
International Conference on Robotics and Biomimetics
December 5-8, 2017, Macau SAR, China

A New Simulation Force Algorithm for Vascular Interventional Surgery Simulation

Dapeng Zhang
Research Center of Precision Sensing and Control
Institute of Automation, Chinese Academy of Sciences
Beijing, China
e-mail: dapeng.zhang@ia.ac.cn

Hanyue Wang
Language Training Department of Chinese Rehabilitation
Research Center for Deaf Children
Beijing, China
e-mail: zdp80@sina.com

***Abstract*—A new simulation force algorithm for vascular interventional surgery (VIS) simulation was presented to calculate the simulation force between the guidewire and vascular wall. Firstly, the topology and space bounding box initialization of vascular model were proposed to accelerate the collision detection between the guidewire and vascular wall, and the gravity coordinate method was applied to detect whether the collision between the guidewire and blood vessels occurred or not. Secondly, the perception of collision separation was adopted to describe the collision response between the guidewire and vascular wall. Thirdly, three restriction elements (vertex, edge, triangular facet) were used to represent the collision response. Furthermore, the bisection method was applied to calculate the simulation force. The VIS simulator for renal artery was developed to validate the effectiveness of the proposed algorithm.**

Keywords—simulation force; vascular intervention; surgery simulation; collision detection

I. INTRODUCTION

Vascular interventional surgery (VIS) is a minimally invasive therapy for the treatment of vascular disease and tumors. Compared with the conventional open surgery, VIS has multiple advantages: 1) it has been established as a curative modality for various kinds of endovascular disease, such as coronary arterial dilatation, aneurysm treatment, cancer local chemotherapy, etc. All the above-mentioned diseases are difficult to cure using conventional open surgery. 2) Surgery haemorrhage is little and patients only need local anaesthesia and can therefore recover more quickly and stay for a shorter time in hospital. In conventional VIS, the surgeon cut an incision in the groin and then insert a guidewire and catheter (the motion of catheter is supported by the guidewire). As the blood vessel is sensitive and brittle, the surgeon must avoid damaging it. Then, under the guidance of feedback force from guidewire tail and fluoroscopic images, the surgeon pushes or rotates the guidewire tail so that the guidewire tip reaches the lesion. To protect the surgeon and patient from the X-ray radiation, the fluoroscopic images are taken intermittently. In addition, the contact force between the blood vessel and the guidewire can not be perceived by novices. Therefore, it need develop VIS training system to improve the operation skills.

Compared with the corpse and patient training, computer-based simulator has two advantages: 1) it is cheap and no X-ray radiation. 2) The surgery operation is evaluated objectively, and operators can repeat the operation until a satisfied result is obtained. Therefore, many researchers have developed computer-based VIS simulator to train the interventional surgeons in recent years. Kent Ridge Digital Laboratories (Singapore) designed a series of VIS simulators [1]-[3]. Dawson and Cotin [4] presented a PC-based simulator that incorporated synthetic fluoroscopy and real-time three-dimensional (3D) interactive anatomical display. The Simbionix Angio Mentor allows surgeons to rehearse a complete VIS procedure on a virtual model generated from a patient's computed tomography (CT) or magnetic resonance imaging (MRI) scan data, and it also provided trainers with tactile feedback [5]. Lenoir et al. [6] described a new approach for real-time deformation of devices such as catheters and guide wires during navigation inside complex vascular networks. Alderliesten et al. [7] proposed an algorithm calculating the propagation of a catheter or guidewire within a vascular system, on the basis of the principle of minimization of energy. Gao et al. designed the Catheter Virtual Reality System for the Robotic Catheter System. The guidewire can be inserted into blood vessels, and the surgeon can take the guide wire and complete the operation [8]-[12]. However, all the researchers mentioned above focused on modelling method of guidewire or catheter and movement algorithm of guidewire within the blood vessel. Few study has been performed on simulation force calculation between the guidewire and blood vessel. However, the perception of simulation force can effectively protect the blood vessel from injuring.

In this paper, a new simulation force algorithm for VIS simulation has been proposed to calculate the simulation force between the guidewire and vascular wall. Our contribution included: 1) the topology and space bounding box initialization of vascular model were presented to accelerate the collision detection between the guidewire and vascular wall, and gravity coordinate method was applied to detect whether the collision between the guidewire and blood vessels occurred or not. 2) The collision separation perception was adopted to describe the collision simulation, and the bisection method was applied to calculate the simulation force. Additionally, three restriction elements (vertex, edge, triangular facet) were used to represent the vascular deformation.

The remainder of the paper is organized as follows. Section II introduces the modelling method of guidewire and blood vessel. Section III proposes the collision detection algorithm between the guidewire and vascular wall. The calculation method of simulation force is presented in Section IV. The algorithm validation and simulation are shown in Section V. Finally, conclusions and future work are given in Section VI.

This work was supported by the Science Challenge Project No. 0006, the National Natural Science Foundation of China under Grant 61303177 and 61673383. Dapeng. Zhang is with the Research Center of Sciences (IACAS), Beijing 100190, China (e-mail: dapeng.zhang@ia.ac.cn). Hanyue.Wang is with the Language Training Department of Chinese Rehabilitation Research Center for Deaf Children(CRRCDC), Beijing 100029, China. (e-mail: zdp80@sina.com).

II. THE GUIDEWIRE AND BLOOD VESSEL MODEL

A. The Discrete Model of Guidewire and Blood Vessel

The guidewire consists of a set of discrete segments which are neither bendable nor compressible. In addition, a 3D carthesian coordinate system (*PQS*) is defined at each node x_i (i from 0 to n-1), as illustrated in Fig.1. When the collision between the guidewire and vascular wall occurs, the adjacent segments rotate around the node. Geometric modeling of blood vessel is reconstructed by 2-D CTA (Computed Tomograph Angiography) slice images, which is scanned as vascular artery is filled with contrast agent. Then geometric model of blood vessel is dispersed into many tetrahedral meshes with springs in their edges. To improve simulation precision, the spring coefficient was derived from a linear finite element method (FEM), which established a link between the spring coefficient and the properties of the vascular materials [13].

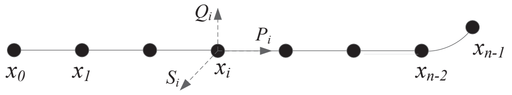
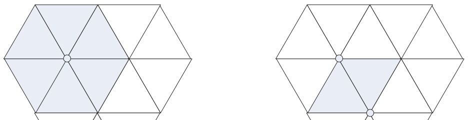


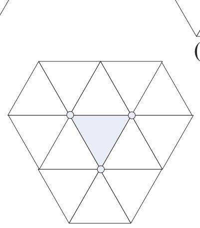
Fig.1. the discrete model of guidewire

B. The Topology and Space Bounding Box Initialization of Vascular Model

Collision detection between the guidewire and blood vessel generally need index all the tetrahedrons of vascular model and guidewire nodes, which obviously can not meet the requirement of real-time VIS simulation. Therefore, the vascular model should be initialized beforehand so as to accelerate the collision detection. The initialization of vascular model consists of two parts: the topology initialization of vascular model and the establishment of space bounding box. The vascular wall was represented by many tetrahedral elements which include a set of vertices, edges and triangular facets. The topology initialization of vascular model would establish the coordinate assembly of vertices, edges and triangular facets. As shown the shadow in Fig.2, the coordinate assemblies of vertices include the adjacent edges and triangle facets, the coordinate assemblies of edges involve the adjacent vertices and triangle facets, the coordinate assemblies of triangle facets include the adjacent vertices and edges. The coordinate assemblies can be directly indexed so as to accelerate the collision detection between the guidewire and vascular wall.



(a) vertex (b) edge



(c) triangular facet

Fig.2. the topology initialization of vascular wall

In addition, the space bounding boxes of vascular model were established to eliminate many unrelated objects so as to accelerate the collision detection. The OBB bounding box was applied to divide the occupied space of vascular model to achieve the approximate representation of vascular branches. Firstly, vascular model was divided into several branches, the various branches were surrounded by space bounding space, as shown in Fig.3. If the bounding box included too many elements (vertices, edges and triangular facets), it would be divided further until the bounding box was only relative with few elements. Secondly, according to the coordinate ranges of space bounding boxes, we established the correlative assembly for each space bounding box. Therefore, when the collision detection between the guidewire and blood vessel was performed, the space bounding boxes were selected according to the coordinates of guidwire nodes, then collision detection algorithm was applied to judge whether the collision between the guidewire and elements (vertices, edges and triangular facets) occurred or not.

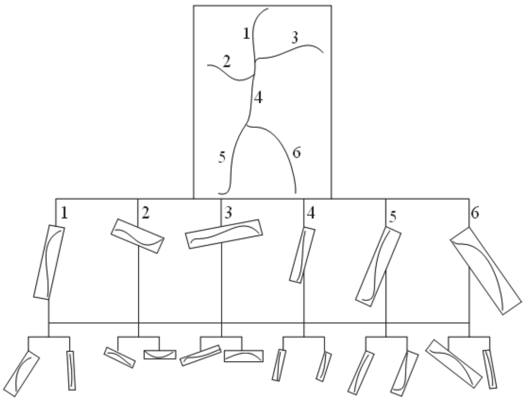


Fig.3. the space bounding box partition of vascular model

III. COLLISION DETECTION BETWEEN THE GUIDEWIRE AND VASCULAR WALL

A. The Collision Separation Perception

The algorithm of collision detection was applied to judge whether the collision between the guidewire and vascular wall happened or not. If the collision occurred, it calculated the collision position and embedding depth. In this paper, the "collision separation" perception was proposed to describe the interactive simulation between the guidewire and vascular wall. The guidewire movements within the blood vessel were controlled by the haptic interactive device, the coordinates of guidewire node is denoted by *HIP* (haptic interactive point). The coordinates of guidewire node in the simulation space were indicated by simulation space point (*SSP*). The interactive simulation was shown in Fig.4, between the time 1 and time 2, the collision between the guidewire and vascular model did not happen, the *HIP* coincided with *SSP*. At the time 2, the collision between the guidewire and vascular model occurred, the guidewire node *HIP* was constrained by the triangular facet *ABC*, the *HIP* of guidewire node separated with *SSP*. When the guidewire moved along the vascular wall, the sequence of constraint element was: triangular facet *ABC* → edge *AC* → triangular facet *ACD* → edge *CD* → triangular facet *CDE* → edge *DE* → triangular facet *DEF* edge *EF* →