Computerized Medical Imaging and Graphics 40 (2015) 160–169

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

A robust and fast approach to simulating the behavior of guidewire in vascular interventional radiology

Haoyu Wang[a], Jianhuang Wu[a,*], Mingqiang Wei[b], Xin Ma[a]

[a] Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, 1068 Xueyuan Boulevard, University Town of Shenzhen, Xili Nanshan, Shenzhen 518055, China
[b] The Chinese University of Hong Kong, Hong Kong SAR, China

ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form 8 October 2014
Accepted 15 October 2014

Keywords:
Interventional radiology
Surgical simulation and training
Guidewire model
Vasculature

ABSTRACT

Interventional radiology (IR) is widely used in the treatment of cardiovascular disease. The manipulation of the guidewire and catheter is an essential skill in IR procedure. Computer-based training simulators can provide solutions to overcome many drawbacks of the traditional apprenticeship training during the procedure. In this paper, a physically-based approach to simulating the behavior of the guidewire is presented. Our approach models the guidewire as thin flexible elastic rods with different resolutions which are dynamically adaptive to the curvature of the vessel. More material characteristics of this deformable material are integrated into our discrete model to realistically simulate the behavior of the wire. A force correction strategy is proposed to adjust the elastic force to avoid endless collision detections. Several experimental tests on our simulator are given to demonstrate the effectiveness of our approach.

1. Introduction

It is well known that cardiovascular disease is the leading cause of deaths worldwide. Interventional radiology (IR) is widely used in the treatment of most cardiovascular disease. With fluoroscopic guidance, physicians can percutaneously insert flexible instruments (such as guidewire, stent, or catheter) into the patient's blood vessel and, from outside the body, manipulate these instruments through the vascular network until reaching the diseased position. Due to the complexity of the vascular network and the counter-intuitive movement of the instruments, performing an IR procedure is difficult, manipulating instruments in a 3D field while viewing them in a 2D screen, and thus requires a high degree of expertise to avoid causing serious injury to the patients.

As a result, physicians require a lot of training to acquire necessary skills such as hand-eye coordination of IR to ensure healthy outcomes. This medical training is traditionally obtained on live patients under the guidance of skilled physicians. However, the apprenticeship training is an expensive, unstructured, time-consuming and resource-intensive process lacking objective feedback [1,2]. Most importantly, learning the skill using real patients is risky and potentially fatal and a breach of ethnics.

Interactive virtual reality based simulators provide promising solutions to overcome many drawbacks of the apprenticeship training. With virtual simulators, trainees can practice the required skills anytime and anywhere without putting patients at risk and exposing themselves to an invasive environment. Moreover, the simulators are reusable. Unlike in vivo experimental training, it can assess the trainees' performance objectively. However, developing a high-fidelity and real-time immersive virtual environment is a challenging task. Several companies or research groups devoted many efforts to virtual vascular IR simulators over the past years [3–6].

The simulation of guidewire and catheter is a crucial component in a vascular IR simulator. In a real vascular IR procedure, physicians manipulate the guidewire to the targeted position by pulling, pushing and rotating the proximal end of the guidewire. The marching direction of the guidewire is determined by the deformation of the guidewire's tip. However, the shape of the guidewire changes all the time as the guidewire is advanced through the vasculature due to its high flexibility. As a consequence, the direction is not easy to control. On the other hand, in different vascular circumstances (e.g. at vessel branches), the physician's manipulation technique is different. Therefore, to provide a meaningful training environment for intervention, it is important to simulate the surgical instruments'

* Corresponding author. Tel.: +86 755 86392213; fax: +86 755 86392299.
E-mail addresses: jianhuang.wu@gmail.com, jh.wu@siat.ac.cn (J. Wu).

http://dx.doi.org/10.1016/j.compmedimag.2014.10.006
0895-6111/

behavior with high fidelity in a complex vascular system. Furthermore, the visual feedback of the simulator should be achieved in real time or within an acceptable limit for the trainees to perform subsequent operations. To address these challenging problems, we present a robust approach to modeling guidewire. Our approach realistically and efficiently simulates the behavior of the guidewire in a wide variety of vasculatures.

Several methods have been presented to simulate the interactive behavior of a guidewire and catheter in a vascular IR procedure. Nowinski and Chui [6] defined the catheter as a series of curved arc segments joined smoothly one after another. This method merges, splits, removes and inserts element curves using the Finite Element Model (FEM)-based representation. However, it is unable to simulate large geometric non-linearity of deformation. Aiming at solving this problem and achieving a more realistic simulation, Cotin et al. [7] employed a set of linked deformable beams with non-holonomic constraints to model the guidewire or catheter dependent on an incremental FEM method. Unfortunately, the simulation accuracy of this method is low due to the accumulating errors generated in each incremental step. Based on this work, Lenoir et al. [8] developed a composite model to simulate the interactive motion of guidewire and catheter by dynamically changing their material properties. Alderliesten et al. [9,10] modeled the guidewire as a set of linked rigid rods with more complex bending energies. Such model can achieve highly accurate simulation, but need to iteratively compute the minimum of the global energy. As a result, this model has a low efficiency and is not suitable for real time simulation. Luboz et al. [11] modeled the guidewire as a hybrid mass–spring particle system and introduced extra bending forces in order to constrain the guidewire to remain within the vasculature. Bergou et al. [12] presented a geometric model of thin flexible rods with arbitrary cross section and non-deformed configuration which can relatively accurately simulate the bend and twist deformations. More recently, Tang et al. [13,14] applied this model to the simulation of guidewire and catheter. However, the simulation accuracy of this method is not high and needs to be improved by invoking additional optimization techniques.

In this paper, an approach to simulating the guidewire's behaviors in vascular structures is presented. Though our approach aims at guidewire modeling, it can be applied to catheter modeling, as the catheter is a wire-like deformable object. Compared with the previous methods, our approach has the following advantages:

Our approach is more robust. The human vascular system is very complex; the inner diameter and curvature of the vessel vary significantly. Most previous methods [9,15,11] simply model the guidewire as rigid rods with invariant length in simulation. It is simple but fails to work in vessels with high curvature and small diameter. In our approach, the guidewire is modeled as rods with different resolutions which are dynamically adaptive to the diameter and curvature of the vessel. Additionally, more material characteristics are integrated into our model based on real guidewires' material property to increase the realism of simulation. This model and the dynamically adaptive discretization strategy make our approach work very well and realistically under different vascular circumstances.

Our approach is faster. In previous methods [10,11], to calculate the elastic force generated by the guidewire colliding with the vessel wall, collision detection needs to be performed frequently. In this paper, we propose a force correction strategy to dynamically adjust the elastic force, leading to reducing the heavy computational burden and saving a great amount of time. In this way, the collision detection is executed only once at each simulation step. Thus, when compared with previous methods, our collision response is more efficient without endlessly repetitive collision detections.

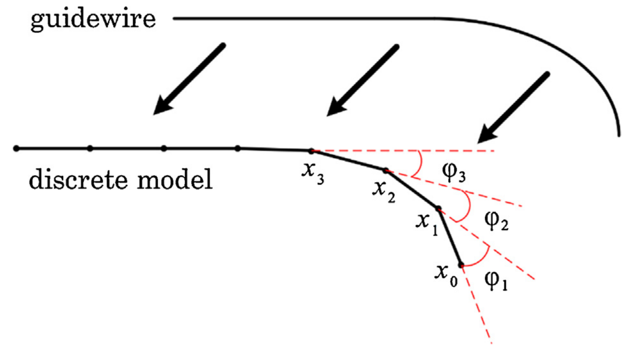

Fig. 1. The guidewire is separated into linked rigid rods and the tip portion is intrinsically curved.

2. Methodology

Our approach is based on quasi-static mechanics in order to ensure a realistic modeling of guidewire propagation. When updating positions of the guidewire, a dynamically adaptive strategy for the discretization of the guidewire is proposed to handle vasculatures with high curvature and small diameter. An efficient and memory-optimized collision detection is performed to deal with the collision between the guidewire and the highly detailed vascular model, which is composed of thousands of triangles. In the collision response, a dynamic force correction strategy is proposed to adjust the external force induced by local displacement of the guidewire.

During the simulation, a local coordinate is attached to every rod of the guidewire to compute local displacements. Main steps of one simulation loop in our approach are summarized in Algorithm 1.

Algorithm 1: Guidewire simulation
Import vascular model
Initialize guidewire (Section 2.1)
Preprocess
While simulating do
Step 1: Wait for control signal
Step 2: Update positions (Section 2.1)
Step 3: Update local coordinates (Section 2.1)
Step 4: Collision detection (Section 2.2)
Step 5: Collision response (i.e., minimizing the total potential energy) (Section 2.3)
Step 6: Update positions (Section 2.1)
End while

2.1. Guidewire modeling

The real guidewire is a flexible, long, thin object. The longest guidewire in IR procedures is 260 cm. In this work, the guidewire is considered as an elastic rod model and is represented as a chain of rigid rods that tend to bend or twist rather than stretch. They are linked by the joint points that form the fixed centerline of the wire. The collision detection and force propagation are based on these joint points.

As shown in Fig. 1, the point $\boldsymbol{x}_i$ represents the joint point that links two rods. The subscript index of points increases from the tip part to the proximal end of the guidewire. A rod is represented by a vector $\boldsymbol{t}_i$ which is defined as follows:

$$\boldsymbol{t}_i = \boldsymbol{x}_{i-1} - \boldsymbol{x}_i, \quad i \geq 1 \tag{1}$$

The angle between two adjacent rods $\boldsymbol{t}_i$ and $\boldsymbol{t}_{i-1}$ is used as a measure of bending energy. To simulate intrinsically curved tips with different curvatures, bias angles (e.g. φ_1, φ_2, $\varphi_3, \ldots,$) as shown in Fig. 1 between the tip rods are defined. And a maximum bias angle φ_m is also predefined for every joint point in order to make the guidewire bend gradually but not abruptly.