A 3D Virtual Reality Simulator for Training of Minimally Invasive Surgery

Shao-Hua Mi, Zeng-Gunag Hou, Fan Yang, Xiao-Liang Xie and Gui-Bin Bian

Abstract— **For the last decade, remarkable progress has been made in the field of cardiovascular disease treatment. However, these complex medical procedures require a combination of rich experience and technical skills. In this paper, a 3D virtual reality simulator for core skills training in minimally invasive surgery is presented. The system can generate realistic 3D vascular models segmented from patient datasets, including a beating heart, and provide a real-time computation of force and force feedback module for surgical simulation. Instruments, such as a catheter or guide wire, are represented by a multi-body mass-spring model. In addition, a realistic user interface with multiple windows and real-time 3D views are developed. Moreover, the simulator is also provided with a human-machine interaction module that gives doctors the sense of touch during the surgery training, enables them to control the motion of a virtual catheter/guide wire inside a complex vascular model. Experimental results show that the simulator is suitable for minimally invasive surgery training.**

I. Introduction

Minimal invasive surgery is a superior treatment paradigm for treating cardiovascular disease and stroke [1]. In a real treatment paradigm, by pushing, pulling and twisting at the proximal end of a catheter/guide wire, the catheter/guide wire is manipulated under X-ray guidance through the abdominal aorta system then into the aortic arch. Comparing with the open surgery, the main advantages of this surgical technique are smaller incisions and less painful. However, these complex medical procedures require a combination of rich experience and technical skills. It is difficult for doctors to control a flexible catheter/guide wire by pushing, pulling and twisting at the proximal end of the catheter/guide wire only under the X-ray projection images. Therefore, in order to complete a minimally invasive surgery, extensive training is required [2-4].

Traditionally, the best training environment on which the hospitals train the learners is mainly based on living animals or actual patients. Developing a real-time interactive 3D computer-aided surgical simulation is desirable and can provide a alternative to traditional training environment. In this way, the virtual reality simulator using a haptic device can help the doctors obtain the core skills of controlling a catheter/guide wire and decrease the risk of errors.

Several virtual reality simulators have been developed or commercialized in projects [5], [6]. However, these systems do not simulate the catheter/guide wire insertion procedures with a complex vascular structure and do not deal with the real-time interactions between a catheter/guide wire and the vascular model or between a haptic device and the catheter/guide wire. In this paper, a 3D virtual reality simulator for training in minimally invasive surgery (in real-time or near real-time) is presented. Comparing with the existing system, this simulator can provide a realistic 3D virtual training environment and support real-time human-machine interactions. The system has the following characteristics: provides realistic and complex 3D vascular models, which is generated from computed tomography angiography (CTA) series in DICOM datasets captured in real patients; provides a real-time virtual catheter/guide wire based on multi-body mass-spring physical model; provides a real-time force computation and force feedback computation module; provides a real-time 3D rendering module and a real-time or near real-time human-machine interaction module [7-9].

Organization of the paper is as follows. Section II outlines an overview of the system. Section III describes the experiments and presents the results. Section IV introduces the future works and concludes this paper.

II. System Overview

Fig. 1 overviews the real-time interactive 3D virtual reality simulator. The system consists of six major components: kernel module, device controller module, 3D vascular model module, catheter/guide wire model module, user interface module and human-machine interaction module.

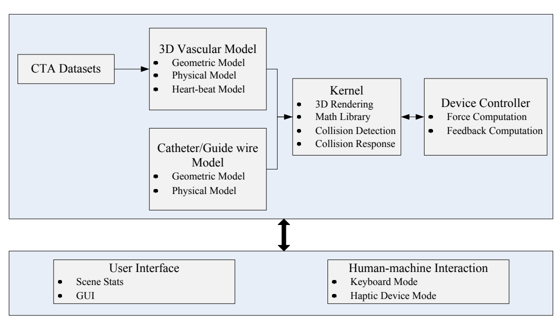

Fig. 1. Overview of the system

The prototype for the simulator is shown in Fig. 2.

A. 3D Vascular Model

A realistic and complex 3D vascular geometric model is imported into the virtual environment of the system, which is generated from computed tomography angiography (CTA) series in DICOM datasets captured in actual patients, as

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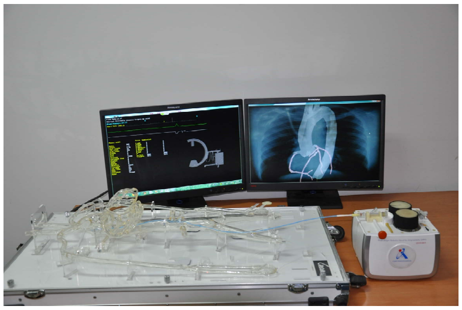


Fig. 2. The prototype for the simulator. The left monitor displays scene statistics, such as FPS, the actual monitoring data of force feedback and 3D X-rays controls, etc. The right monitor displays the real-time interactive 3D simulation procedures.

shown in Fig. 3. The original CTA series are acquired by a 128-slice Siemens SOMATOM Definition Flash CT and the datasets have been segmented using ITK library [17]. Then, by using the physical modeling function, the 3D geometric model is turned into 3D physical model.

Fig. 3. A 3D vascular geometric model of 33,582 triangles generated from a real patient database.

The visualization of the coronary vasculature is one of key tasks of the system, and in order to achieve real-time realistic effects, we add a heart-beat model module into the system, as shown in Fig. 4.

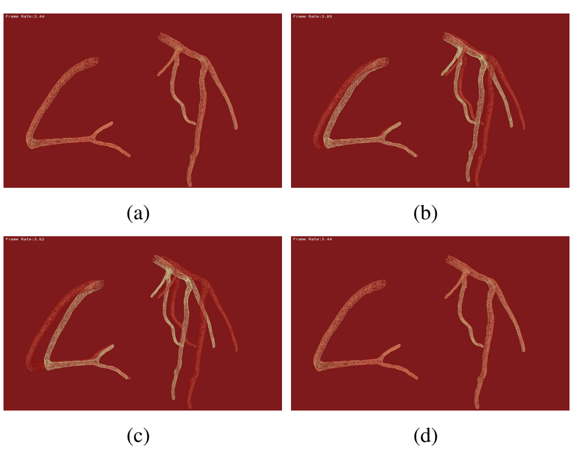
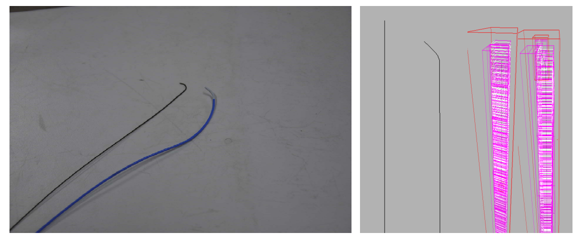


Fig. 4. Heart-beat Model. In this module, we use coronary-beat in place of the heart-beat model. Firstly, the geometric objects are stored as series of vertex. Then, in each key frame of a simulation, the position of vertices are then charged between these stored positions.

B. Catheter/Guide Wire Model

For a real-time interactive 3D simulation, modeling a realistic deformable object is a difficult work [10]. By contrasting advantages and disadvantages to the existing works proposed in [11-13], we present a multi-body mass-spring model for the catheter/guide wire simulation in this system. The virtual catheter/guide wire is composed of three parts: tip, link and body. The tip and the body are represented by mass-spring model, and the link is a rigid body [16]. Fig. 5 shows the simulation results of the catheter/guide wire .



(a) (b)

Fig. 5. (a) A real catheter and guide wire model. (b) The virtual catheter/guide wire and its AABB in the system.

C. Kernel Module

The kernel module is in charge of creating a main function and providing APIs for the entire simulation procedures. This module consists of four sub-modules.

- Collision detection and collision response: the collision detection in the system is divided into broad phase and narrow phase [14]. A combined algorithm based on median point algorithm and continuous collision detection algorithm is proposed in the system [16]. Once a collision is detected, the system needs to call the collision response algorithm in each loop and the virtual catheter/gudie wire is moved to a new equilibrium determined by the motion equations.
- Math library: the math library provides important data structures, basic mathematical computations and effective supports for device controller module.
- 3D rendering: the 3D rendering module is in charge of providing 2D or 3D displays and special effects. Fig. 6 shows an effect analogous to X-ray image.

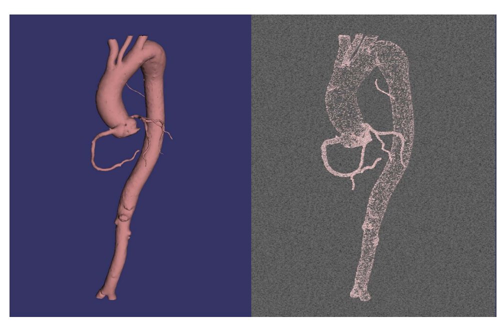


Fig. 6. X-ray simulation. A 3D vascular model in the 3D rendering (left) and the same model in the special effect rendering mode (right).

D. Device Controller

The device controller module is responsible for creating link between the haptic device with the kernel module, and providing real-time force computation and force feedback computation supports for the system.

E. User Interface

The system can be integrated with visualization software toolkits by using the user interface module. The module includes a real-time 3D scene stats module and a GUI module. By using the user interface, kinds of GUIs can be integrated into the system, such as CEGUI, GLUT and QT. Fig. 7 displays the real-time 3D scene statistics of a running application.

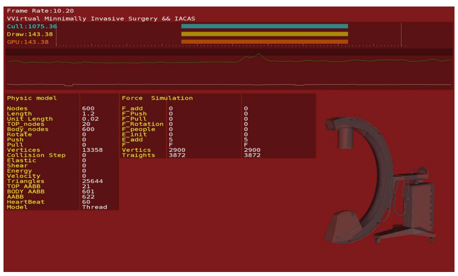


Fig. 7. Real-time 3D scene statistics. A screen from user interface that shows C-arm X-ray image controls and dynamic monitoring stats.

F. Human-machine Interaction

The human-machine interaction module provides two modes : the haptic device mode and the keyboard mode. Under the haptic device mode, doctors can use a haptic device to control the motion of a virtual catheter/guide wire inside the vascular model by pushing, pulling and rotating at the proximal of the catheter/guide wire [15]. At the same time, the haptic device provides adequate force and force feedback, which are generated from the device controller module. The haptic device using in the system is shown in Fig. 8. However, the keyboard mode is designed for system test and parameter setting purposes.

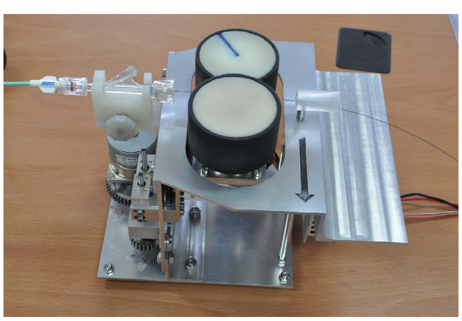
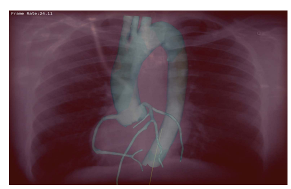


Fig. 8. The prototype of the haptic device in the system. The haptic device can manipulate a catheter/guide wire and provide adequate force feedback.

III. Experiments and Results

In order to demonstrate the system is realistic and efficient, numbers of experiments are conducted to show the results of the simulation procedures in this paper. The virtual catheter/guide wire modelled using 620 nodes is tested with a realistic and complex 3D vascular model of 25,466 triangles. The simulation is performed on a PC with 3.1GHz processor and 2GB RAM, and in the initial phase of the application development, all the experiments is performed under the keyboard mode for system integration test purposes. Fig. 9 is the results of a virtual catheter/guide wire travels through the 3D vascular model and moves towards a target allocated at the coronary artery by pushing the catheter/guide wire. The behaviors of a virtual catheter/guide wire by pulling and rotating is described in [16]. The relationship between the FPS and the inserted length of the virtual catheter/guide wire is shown in Fig. 10. A FPS greater than 20 is normally considered to meet real-time requirements. The worse case is about 18 FPS.

(a)



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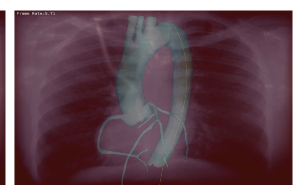

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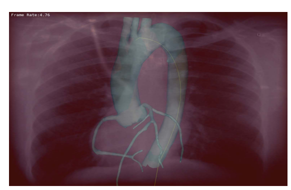

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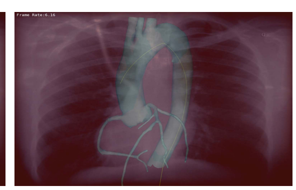

(e)

Fig. 9. Simulation of the catheter/guide wire insertion procedures.

IV. Conclusions

In this paper we propose a real-time interactive simulator for core skills training in minimally invasive surgery and describes its major components. The experimental results show that the system is capable of simulating the behaviors of the catheter/guide wire inside the complex vasculature. For a 3D virtual reality simulator, how to integrate different components into the system is a real challenge. Extending the

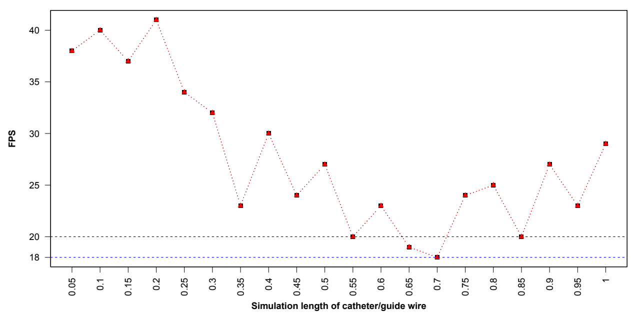

Fig. 10. Line chart (R). This chart shows the relationship between the FPS and the inserted length of the virtual catheter/guide wire. A FPS greater than 20 (black line) is normally considered to meet real-time requirements. The worse case is about 18 FPS (blue line).

existing works and developing a complete simulation system are the future works.

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