Proceedings of 2014 IEEE
International Conference on Mechatronics and Automation
August 3 - 6, Tianjin, China

An 3D Interactive Virtual Reality Software Toolkit for Minimally Invasive Vascular Surgery

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***Abstract*—Recently, much more attention has been paid to the development of minimally invasive vascular surgery. Simulating behaviors of a catheter/guide wire in a realistic 3D vascular model for minimally invasive vascular surgery is a challenging subject. One of the main problems for an 3D computer-based virtual reality simulator is how to design a software toolkit primarily targeted to medical simulation. In this paper, we describe an 3D interactive virtual reality software toolkit and present an example of application to a virtual minimally invasive vascular surgery procedure. Finally, experimental results are given to show that the 3D interactive virtual reality software toolkit is effective and promising.**

***Index Terms*—Simulation, mass-spring model, catheter/guide wire, software toolkit, minimally invasive vascular surgery.**

I. INTRODUCTION

Minimally invasive vascular surgery is a recent interventional technique for treating heart disease. The computer-base virtual reality minimally invasive vascular surgery system provides a solution to help the trainees acquire the core skills of steering the catheter/guide wire and decrease the risk of errors. It is admitted that the development of the computer-base real-time virtual reality minimally invasive vascular surgery system is promising. The key aspect central to the simulator is realistic and fast simulations of a catheter/guide wire with complex vascular model. The success of the system depends on how to develop the real-time physics and graphic rendering simulation algorithms. Therefore, designing and developing a real-time software toolkit for virtual reality surgery system is a challenging subject [1], [2].

Several software toolkits for medical simulation have been developed in previous projects, such as SOFA [9]. SOFA is a famous open source C++ library for medical simulation and can be used as an external library in another virtual reality simulation program[3]. However, these different open source library are generally limited by given projects and difficultly adapted to the simulation of minimally invasive vascular surgery. In this paper, we propose a new software toolkit based on an open source C++ library called osgBullt [8], which is a group of open source software tools for applications that use both Bullet [7]and OSG[6]. The new software framework is different from traditional osgBullt library in an important way: the new software package provides soft body dynamics simulation module.

The goal of the new software toolkit is to develop an interactive 3D virtual reality training simulator for minimally invasive vascular surgery. The main objectives of the software framework based on osgBullet are:

- Provide a soft body dynamics library for medical simulation.
- Provide a high performance 3D graphics toolkit based on OSG.
- Provide a professional collision detection library based on Bullet physics engine.
- Provide a software interface for scene and user interaction (haptic device).

Oraganization of the paper is as follows: the software architecture is presented in Section II. The main features of the new software toolkit is described in Section III. Section IV and Section V present an application example Section. Conclusion and future works are introduced in Section VI
.

II. SOFTWARE FRAMEWORK

The software framework based on the new software toolkit is written in standard C++ and makes use of the Bullet physics and OSG (OpenSceneGraph). The Bullet physics is a professional open source collision detection, rigid body and soft body dynamics library [4, 5]. Bullet collision detection can be used on its own as a separate SDK without Bullet dynamics. The main task of Bullet in our medical simulation project is to perform collision detection and provide basic soft body dynamics. The OSG is open source, real-time graphics middle-ware used by application developers in fields that range from visual simulation to virtual and augmented reality, to medical and scientific visualisation, to education and games [10]. The OSG is written in Standard C++, taking advantage of the standard template library for containers and uses the scene graph approach to representing 3D worlds as a graph of node that logical and spatially group subgraphs for behaviour and high performance. OsgBullet is a set of tools to facilitate developing software that uses Bullet for physics simulation and collision detection, and uses OSG for rendering.

The OSG library, the Bullet library and the osgBullet library are used in the new software framework. The software framework is constituted of five modules: graphics rendering engine module, physics engine module, interface module, math module and core module, as shown in Fig. 1. The graphics rendering engine module based on OSG provides 3D graphics application programming interface and interactive user interface; The physics engine module based on Bullet provides collision detection and soft body dynamics; The interface module includes load .bullet file module and GUI module; The math module in charge of computing the force simulation and the force feedback; The core module in charge of providing useful APIs for applications that use OSG, Bullet and osgBullet, especially for basic soft body dynamics and simulation [11-13].

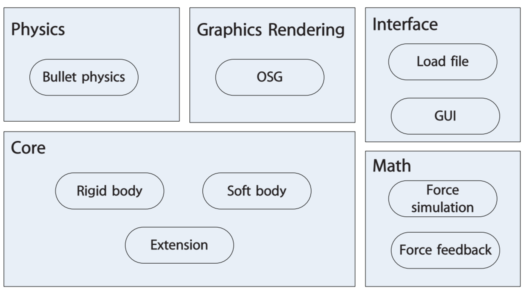


Fig. 1. System modules.

III. Features

A. Scalability

The new software platform is implemented in C++ and uses three open source C++ software library: OSG, Bullet and osgBullet. The above mentioned library are free for commercial use under the GNU Public License (LGPL) and ZLib license. The new software toolkit is cross platform running on many platforms including Linux, Mac OSX and Windows [6]. OpenGL is supported making it available for both old hardware and latest mobile devices. Design Patterns based on OSG are used throughout the new software toolkit making it easier to maintain and improve performance.

B. Creative Effects and Animating

To create a realistic enough effect for 3D virtual reality medical simulation, the depth buffer and the night vision effect are added into the new software toolkit. Some parts of code is from OSG cookbook. Fig. 2 shows the simulation of an 3D vascular structure under X-ray imaging by used the new software toolkit. At the same time, the particle effects based on OSG is added to the software toolkit, as shown in Fig. 3.

Morph target animation is an 3D computer animation techniques. In a morph target animation, a deformed object is stored as a series of vertex. In each key frame of an animation, the vertices are then changed between these stored positions [6]. In the project of medical surgery simulation, the morph target animation techniques are used to simulate the heart-beat model.

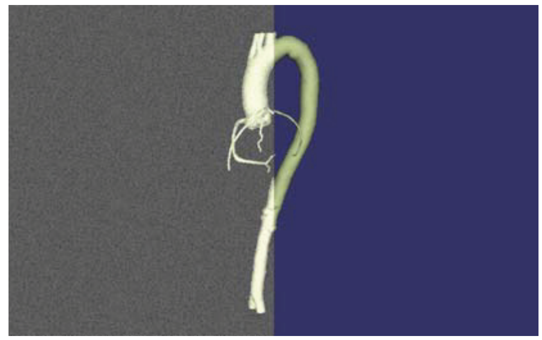


Fig. 2. X-ray simulation.

Fig. 3. Soft body simulation in snow using particle effect.

C. Soft Body Dynamics

Soft body dynamics is a field of computer graphics that focuses on physical simulation of the motion and properties of deformable objects. Although the osgBullet library is the result of collaborative work between OSG and Bullet, the osgBullet library does not support for soft body physics. The new software toolkit adds the soft body simulation module into the software platform, and integrates the soft body collision shapes into OSG scene graphs. The soft body dynamics module based on Bullet provides rope simulation, cloth simulation and volumetric soft bodies. The simulation of soft body can be obtained by using the following approaches: mass-spring model, rigid-body based deformation and energy minimization methods (The software framework does not currently support finite element simulation). A example of soft body dynamics simulation (cloth simulation) is shown in Fig. 3 [14,15].

D. User Interface

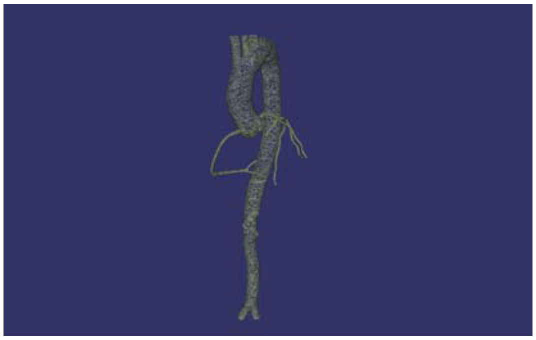


Fig. 4. The physical model of the 3D vasculature file.

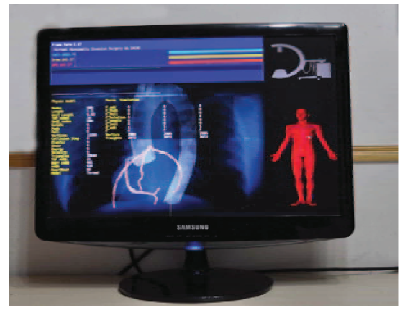
The new software toolkit can read and store an 3D model in the cross-platform binary .bullet file format by configured with a third-party plugin. In the project: the 3D virtual reality simulator for minimally invasive vascular surgery, we use the .bullet file format to load a complex and realistic 3D vasculature model of 2,5466 triangles, which is selected from 128 computer tomography database of a real patient, as shown in Fig. 4.

The project can be integrated with windowing system by using the window handle to the graphics rendering engine module based on OSG. OSG provides many kinds of solutions to integrate OSG with different GUIs, such as CEGUI, GLUT and Qt [1]. In addition, the new software toolkit enables users to create more views on multiple screens and more graphics contexts on one view, as shown in Fig. 5.

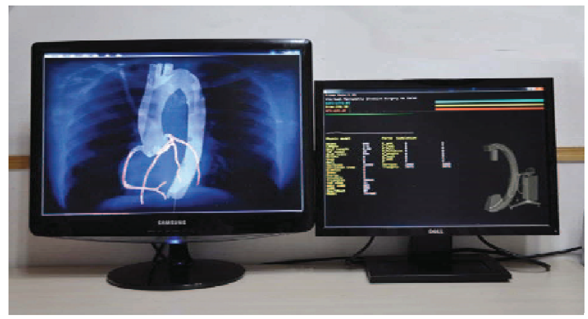
The new software toolkit provides many kinds of man-machine interactive mode. Because the goal of the new software toolkit is to develop an interactive 3D virtual reality training simulator for minimally invasive vascular surgery, the simulator is controlled by two ways: keyboard interactive mode and haptic device mode. However, in the initial phase of the application development, the system is controlled by a keyboard interactive mode for software test purposes. The robotic carheter/guide wire operating system, which is used as the haptic device, is simple introduced in our previous work [17].

E. Multithreading

The new software toolkit based on OSG library contains a threading library, OpenThreads, which is a lightweight cross-platform thread model [1]. It is intended to provide a minimal and complete object-oriented thread interface for C++ programmers. The multithreading technique can facilitate and accelerate the speed of the applications. An application example of the multithreading technique is presented in our previous work [17].



(a)



(b)

Fig. 5. User interface and scene information.

IV. Application to Simulating Minimally Invasive Vascular Surgery

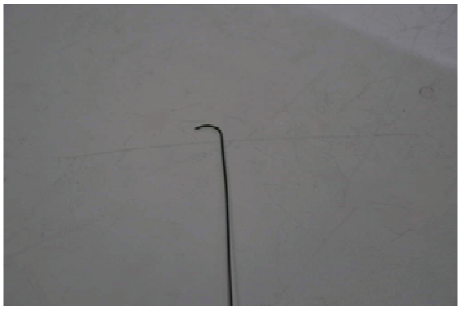
The goal of the new framework is to develop an interactive 3D virtual reality training simulator for minimally invasive vascular surgery. In this section, we present an application used to simulate a catheter/guide wire in 3D vascular models.

A. Physics Model

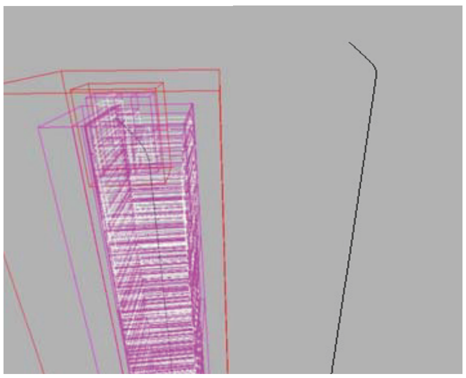
A multi-body mass-spring method used basic mass-spring model to simulate the catheter/guide wire is developed in the medical surgery simulation system, as shown in Fig. 6. The multi-body mass-spring model is described in the previous work [17]. We test the virtual catheter/guide with a complex and realistic 3D vascular model selected from 128 computer tomography database of real patients [18]. Fig. 4 shows the physical model of the 3D vascular model.

B. Collision Detection

The collision detection algorithm of the new software toolkit based on Bullet physics library is divided into broad phase and narrow phase. Considering that the collision detection algorithm requires reliability and real-time performance, we present a combined algorithm which is based on median point triangle algorithm and continuous collision detection algorithm. The related research is in detail introduced in the previous work [19].



(a)



(b)

Fig. 6. The real guide wire and the virtual catheter/guide wire.

(a)

(b)

Fig. 7. Collision response test.

C. Collision Response

Once a contact is happened, maybe under the action of forces, the catheter/guide wire nodes must be moved to a new equilibrium determined by the motion equations using the math module. At the same time, how to avoid the nodes of the catheter/guide wire from going through the margin of the 3D vascular model need be solved by the application in the collision response step. The collision response algorithm is composed of force computation and optimization [19]. Our simulator uses haptic device as man-machine interface device. However, in the initial phase of the application development, the keyboard mode is provided for the new software toolkit test purposes. Fig. 7 shows the simulation results that user uses a keyboard to steer the virtual catheter/guide wire to travel through an 3D blood vessel model (3D blood vessel model is parts of the abdominal aorta generated from 128 CT dataset) by pushing at the proximal end of the virtual catheter/guide wire.

D. Force Computation and Force Feedback

Both collision response and force feedback need to call the force computation algorithm in each frame, which is main part of the math module. When a collision detection is detected, the force computation algorithm must be called by the collision response and the virtual catheter/guide wire reaches a new equilibrium determined by their kinetic equation. Then, the force feedback algorithm invokes the force feedback function and pass the results to the haptic device. In other word, by using the force computation algorithm and the math module, the position of the virtual catheter/guide wire and the results of force feedback are updated at each loop. More related presentations is described in [17]. Fig. 8 shows the main computation stages in the new software toolkit pipeline.

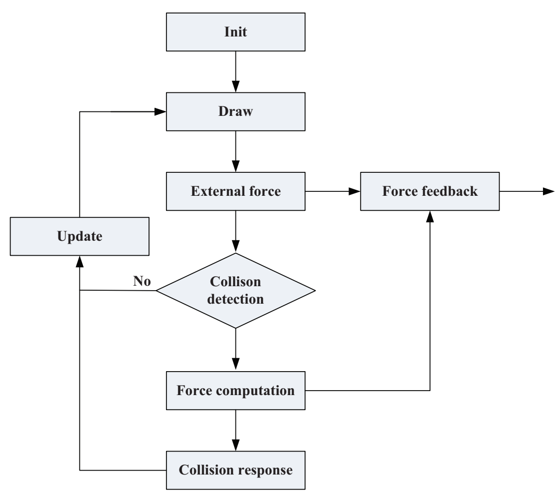


Fig. 8. Program flow chart.

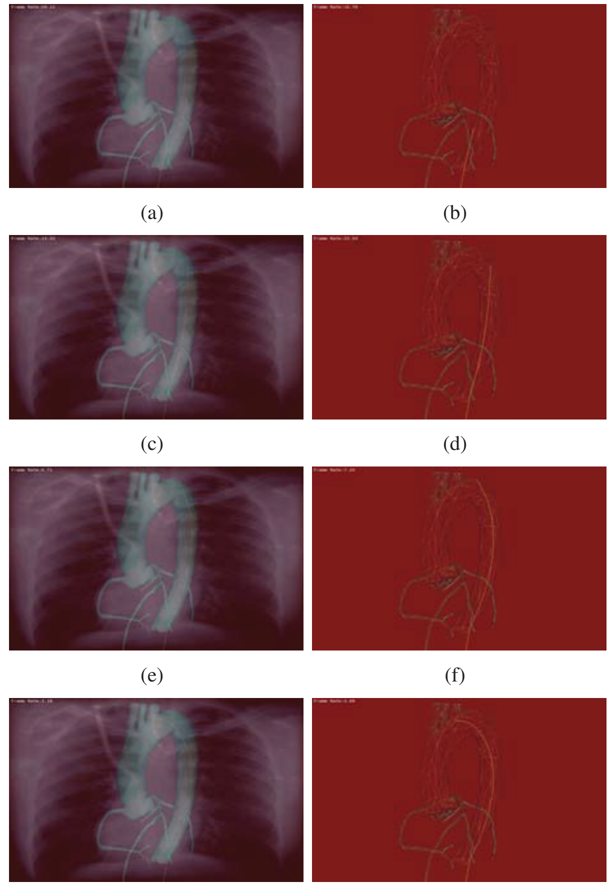
E. Optimizer

We test the virtual catheter/guide wire modelled using 620 nodes with a high detail 3D vasculature model of 2,5466 triangles. In each frame, computation time is spent in collision detection, collision response and the force feedback. For the real time medical simulation system, we need to speed up the execution of the programs. The multithreading technique based on OSG is used to accelerate the medical surgery simulation, as introduced in [19].

V. Experimental Results

We import a high detail 3D vasculature model of 2,5466 triangles into the virtual environment, which is presented in Fig. 9. The virtual catheter/guide wire is inserted into the virtual 3D blood vessel model and use a keyboard to steer the catheter/guide wire by pushing at the end of the instrument. The virtual catheter/guide wire is composed of 620 nodes and the length of it is 1.2m. The software platform runs on a PC with 3.1GHZ Core i3 processor and 2GB of RAM [16]. The Fig. 9 is the result of the virtual catheter/guide wire with the high detail 3D blood vessel model.

Fig. 9. Virtual environment for minimally invasive vascular surgery and scene information.



(a) (b)
(c) (d)
(e) (f)
(g) (h)

Fig. 10. Simulation of a catheter/guide wire push procedures.

VI. Conclusions

In this paper, we present the main features of a new software toolkit, and describe an example of the new software toolkit in medical simulation: virtual minimally invasive vascular surgery. The test results show that the new software toolkit is suitable for simulating the catheter/guide wire with a complex and realistic 3D blood vessel model. The relationship of the simulation length of a catheter/guide wire to FPS (frame per second) is shown in Fig. 12.

- Generally speaking, for a real-time system, 20 FPS ensures the application runs smoothly on a PC.
- Unfortunately, the worst case is about 15 FPS in Fig. 12. The value means when the catheter/guide wire meets the vessel bifurcation, the simulation is unlikely to run smoothly.
- Fig. 12 shows the multithreading technique reduces the processing time of the simulation.

The new software toolkit is in development, and new features is going to be added.

- In the test system of the software platform, the catheter/guide is controlled by a keyboard mode. Improving the software framework and adding the haptic device module are two aspects of the future works.
- Developing different physics dynamcis model of the catheter/guide wire in the 3D virtual reality simulator is another work.
- Supporting parallel processing using GPU acceleration is a new challenge.

Acknowledgment

This research is supported in part by the National Natural Science Foundation of China (Grants 61225017, 61203342 and 61203318), and the Beijing Natural Science Foundation (Grant 4132077).

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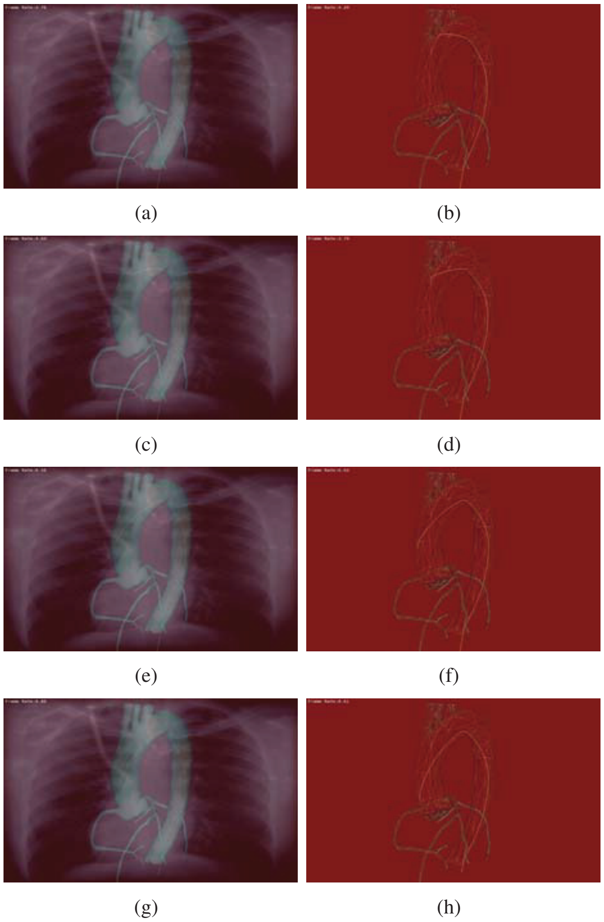

Fig. 11. Simulation of a catheter/guide wire pull procedures..

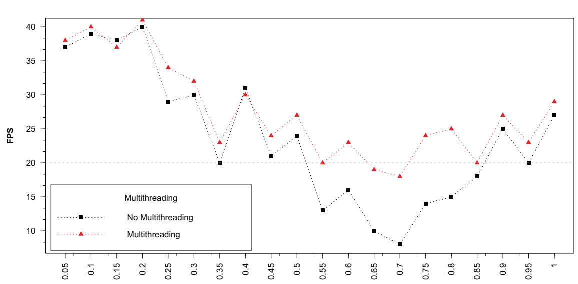

Fig. 12. Line chart: This chart shows the relationship between the FPS and the inserted length of a virtual catheter/guide wire.

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