Proceedings of 2017 IEEE
International Conference on Mechatronics and Automation
August 6 - 9, Takamatsu, Japan

The Virtual Reality Simulator-based Catheter Training System with Haptic Feedback

Shuxiang Guo[*1*2]
[*1]Key Laboratory of Convergence Medical Engineering System and Healthcare Technology,
The Ministry of Industry and Information Technology,
School of Life Science and Technology

Beijing Institute of Technology
Haidian District, Beijing, 100081, China
guo@eng.kagawa-u.ac.jp

Miao Yu[*3], Yu Song[*3], Linshuai Zhang[*3]
[*2] Department of Intelligent Mechanical Systems Engineering

[*3] Graduate School of Engineering

Kagawa University
Hayashi-cho, Takamatsu, 761-0396, Japan
{s16g526,s15d641,s16d502}@stu.kagawa-u.ac.jp

Abstract - **The endovascular surgery benefits patients due to the miniature wound and fast healing, but to achieve this kind of goal need the doctor with superb skill in order to not made damage to the patients. A training system is desperately in need. The training system is cooperated with VR simulator system, which could simulate the movement of the catheter. To get the novice surgeons get trained, a controlling device makes training system effective. At the same time, the feedback system also provides advantages for training. The performance is evaluated from the displacement in VR system and force feedback from haptic device. The results demonstrate that the operation error is less than 10%. The purposed training system provides a effective way which combined the VR catheter system and force feedback system.**

Index terms - ***Virtual-reality simulator; Haptic force feedback; Training system; Collision detection***

I. Introduction

Endovascular surgery has been the focus of many recent studies due to its advantages like small incisions, less blood loss, quicker recovery over the traditional surgeries. Even some commercial companies like Hansen Medical and Catheter Robotics Inc. have developed catheter robotic systems such as Sensi (Hansen Medical) [1],[2] and Amigo (Catheter Robotics Inc.) [3] to assist surgeons. But the high costs of purchase and maintenance limit commercial products use widely. Therefore, a number of investigators have put their efforts on catheter robotic system development. Arai et al. [4] at Nagoya University used the linear stepping mechanism inspired by mechanical pencil to move the catheter step by step. Yogesh et al. [5] developed the remote catheter navigation system which allowed surgeons operating real catheter. Furthermore, our lab designed master-slave catheterization system [6],[7] is displayed in Fig.1. The tele-operated system design protected surgeons from fluoroscopic X-ray exposure during catheter guide intervention and the design of catheter manipulator was to imitate surgeon's hand inserting catheter procedure.

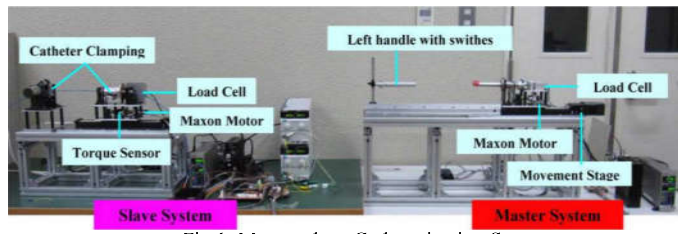

Fig.1 Master-slave Catheterization System

But nowadays, many novice surgeons are need to be trained due to the high cost of the catheter robotic system. Surgeons have to be trained in order to decrease the dangerous for patients while the surgery. Traditionally, the training is by mentored method and with the extra excises on animals or anatomic phantoms. But this kind of training is lack of feedback and the experienced surgeons got is unstructured. Considering this, a virtual-reality based training system is a promising way to help novice surgeons with a risk-less environment. Moreover, the evidence from Yale and Grandtcharov showed that VR-trained participants made significantly fewer intraoperative errors than the standard-trained participants.

Apart from these complete systems, some researchers focused on building up the VR system, such as graphic rendering, model behavior of vascular (tissue) or instruments. The virtual-reality simulator began with 3D volumetric model construction. Through the acquired image data, the vascular geometric model was generated [14],[15]. To strengthen the realistic visualization, vascular deformation was essential. The mass-spring model was a common method in real-simulator [16] because of its superiority in computation. Compared with mass-spring model, another widely used method was finite element [17]. To take advantage of both methods, [18],[19] proposed to use mass-spring model for simulation but the spring coefficient was determined by finite element method to improve precision. Except for tissue model construction, the catheter and guide wire modeling was studied by Tang et al.[20] who used elastic rod model for guide wire simulation. But this method was only suit for slender body. [21] presented

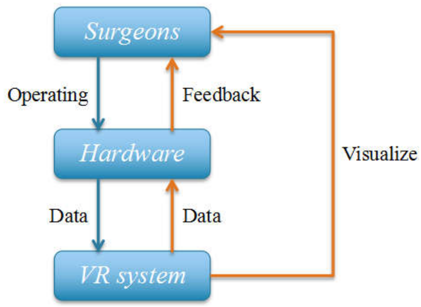

Fig.2 schematic of the system

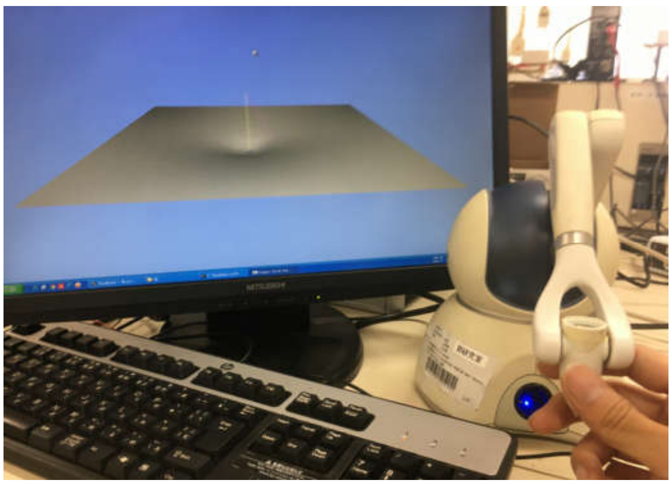

Fig.3 Phantom Omni Device with force feedback test

a hybrid modeling approach which used nonlinear elastic cosserat rods for guidewire shaft and generalized bending model for flexible tip.

So many effort have been made in the recent years, there's also some of the defects need to be solved. The former VR system research is how to replicate the realistic environment of the surgery, such as building the well-made blood vessel model and catheter model. But to replicate the novice surgeons' action and make them feel the feedback using the VR system is what researchers should pay more attention.

With consideration above, we built up a device simulating the movement of the novice surgeon which closer to the surgery environment. The structure of this paper is organized by following parts: First part is the relative researches and the purpose of this research. Then the design and controlling part is in section II. Section III is experimental setup and evaluation. Last part of the paper have given the conclusions.

II. Proposed Training System

A. Overview

The proposed controlling system is consists of two parts. The first part is hardware part, this part is the novice surgeons' mainly operating part. When the novice surgeons are operating the device, this part will receive the moving and rotating action of the surgeons' operation, then transport the data to VR system. The second part is VR system, from the data collected from hardware, it make the moving or rotating of the catheter visible, that makes surgeons understand thier own operating, when the collision happened, VR system also issue data to hardware as feedback. The schematic of the system was shown in Fig.2. In the VR platform, the vascular geometrical model and physical model have been done by our previous works [22][23].

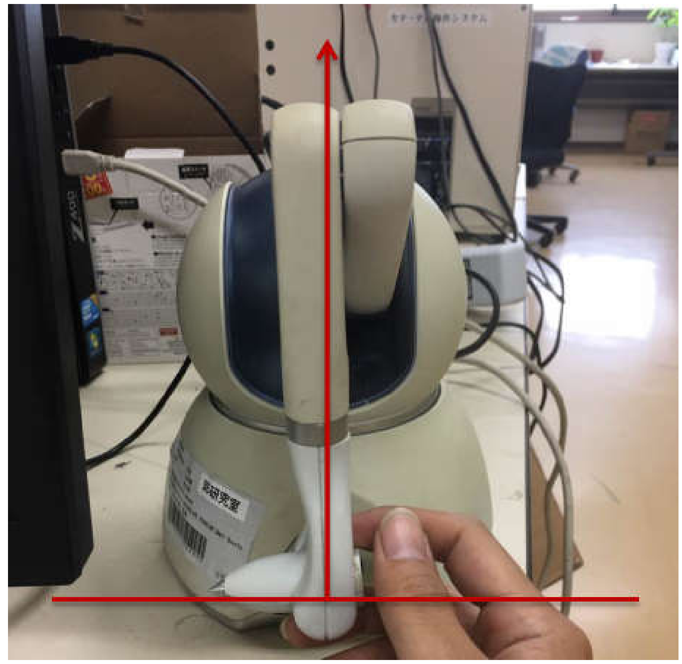

Fig. 4 Steady position of Phantom Omni device

B. Hardware

For hardware part, the haptic device we choose is Phantom Omni. The Phantom Omni enhances productivity and efficiency by enabling the most intuitive human/computer interaction possible, the ability to solve problems by touch.

The Phantom Omni model is the most cost-effective haptic device available. The Phantom Omni system's high fidelity force feedback senses motion in 6 degrees of freedom providing the best, most realistic 3D Touch sensation for any application. This device could help us to feel the point of the stylus in all axes, and track its orientation (pitch, roll and yaw).

Considering the attributes of Phantom Omni, we purposed a controlling method to control the VR system and did some programming work based on it. First, the tip of the device is keep steady as Fig.4, until the novice surgeon give the device a axis force to make the tip get displaced, at this time, the device will also gives reversed force to against the novice surgeon as resistance as Fig.5. The more displacement Phantom Omni device get, the more resistance force it gives. That means, where ever the novice surgeons move it, the resistance force could always drive the Phantom Omni device to the steady position.

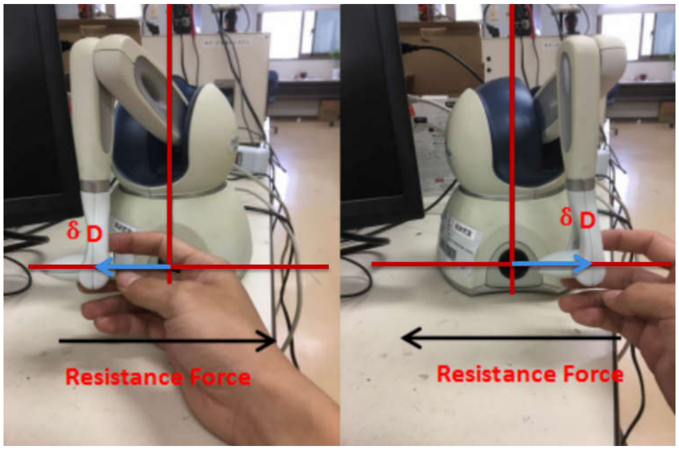

Fig.5 The relationship of the direction of resistance force and displacement

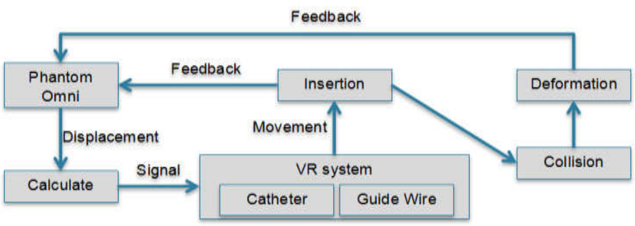

Fig.6 VR platform work flow chart

Assume the trainee moving the catheter forward. The trainee's hand exerted pulling force on the Phantom Omni device, that displacement is also measured by it, then sent the signal to the VR system. After that, the computer that connecting the Phantom Omni device calculates the displacement and gives how the resistance force drives. If there is any collision happened in VR training system, the Phantom Omni device also could give another resistance force and vibration to trainee's hand. The formula of the resistance force is followed as:

$$F_R = \Delta D \times k_r \tag{1}$$

In Eq(1), F_R is resistance force, ΔD is the displacement from steady position, k_r is a constant which can be modified in the programming.

At the same time, the displacement could also give a force to the VR catheter system. By force feedback, novice surgeons could feel the catheter is in there hand. Our team made this is in order to help novice surgeons could feel the force feedback to get better training experience and effect.

C. Program

As the visual assistance for training system, the VR is capable to simulate the scenario where the virtual catheter moves in the vessels according to physician console side's commands. At the same time, the image information related directive notification module (DNM) is integrated into VR platform. On one hand, the DNM aims to enhance the perception of catheter tip acting area and inform the trainee maneuvering catheter in relatively safe space. On the other hand, the DNM is able to develop the hand-eye coordinate by cooperating with the Phantom Omni haptic device.[8] The visualization thread is circulated and contributes to exhibit the latest motion of catheter and vessel. The VR platform work flow is displayed in Fig.6. The visualization thread is circulated and contributes to exhibit the latest motion of catheter and vessel.

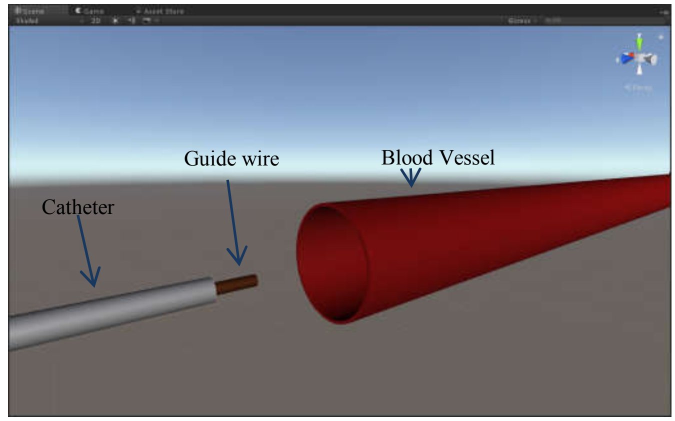

Fig. 7 New 3D model based on Unity3D

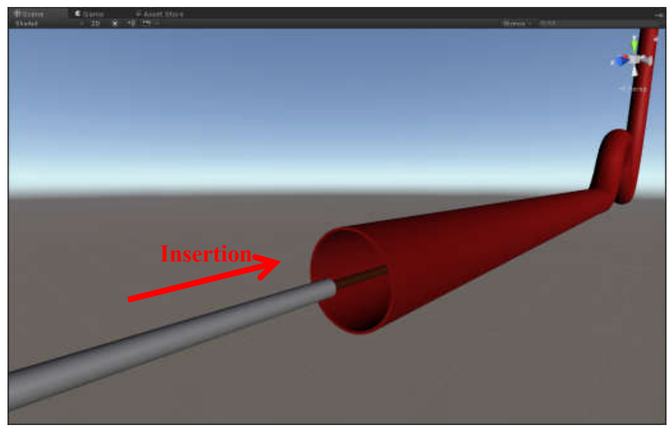

Fig. 8 The insertion of catheter and guide wire.

The programming tool we choose Unity3D, Unity could create any 2D or 3D processing. It is easy to deal with, could make the processing highly-optimized. What's more, Unity has integrated services to speed up the development process, optimize the processing, connected with an audience. Based on these we build a new 3D model based on Unity3D, which exists both catheter, blood vessel and guide wire was shown in Fig.7.

Blood vessel 3D model was based on a real glass model, which consist with straight blood vessels, curved blood vessels, lesions and bifurcation of the blood vessel. These four characteristics are very representative during the training of the endovascular surgery.

The movement of the catheter and guide wire in VR system rely on the signal from the Phantom Omni device, when the displacement happens, the computer will calculate the displacement value and the catheter or the guide wire get a signal then get a speed due to the displacement's value, that means the catheter or guide wire get a action of insertion as Fig.8. We didn't choose accelerate as a dimension to control the catheter and guide wire because of the acceleration is uncontrollable, speed is more easy and intuitive to compare with accelerate.

After this, we build a tele-communication system in order to achieve tele-operating or tele-training. At the same time, the program also returns data to host computer in order to give signal to Phantom Omni device as a force feedback system. If the collision of the guide wire and blood vessel happened, the program will return a set of data to the Phantom Omni device that to describe the feedback of the VR system by resistance force and vibration.

III. Experiment and Evaluation

The VR simulator was executed on 64 bit computer with four processors (Intel 3.07GHz) and 16GB RAM. Using the version of 5.5.0f3 of the Unity 3D programming software. Using the blood vessel model is based on a glass blood vessel, import it into the Unity 3D during the experiment. The virtual catheter was simulated by a chain of 1 mm diameter and 5mm long cylinders with the angular limited joints. In the Unity 3D, the safety range was set exceeding 2.5mm and warning range was beyond 1mm but less than 2.5mm. Because of the attributes of the mesh collider of the Unity 3D, the collision detection is less than 1mm in average. In the VR training system, the ways to transform the data with Phantom Omni device is by TCP/IP protocol.

To assist the evaluation of the experiment, we do 5 times of operation in different displacement of the Phantom Omni device, record the data by VR training system as Fig.9. The Unity 3D software could provide the 3 axis of the catheter or guide wire. Then comparing the real moving distance with it in VR system to verify the accuracy of the device. The Phantom Omni Device displacement is by reading the encoder and reading the position which the Phantom Omni device sent to the computer. The results were shown in Table.1.

We found that there is some error during the experiment, for each time period, the real average speed is lower than the speed we purposed. The error is much bigger when the displacements get bigger. The reason we found why there is error is because of the latency, it is caused that the data could

Table.1 5 times experiment displace result

Experiment No.	1	2	3	4	5
Displacement of Phantom Omni (mm)	5	10	15	20	25
Purposed speed in VR (mm/s)	1	2	3	4	5
Real average speed in VR (mm/s)	0.97	1.94	2.90	3.87	4.82
Displacement in VR traning system in 5 sec (mm)	4.85	9.70	14.50	19.35	24.10

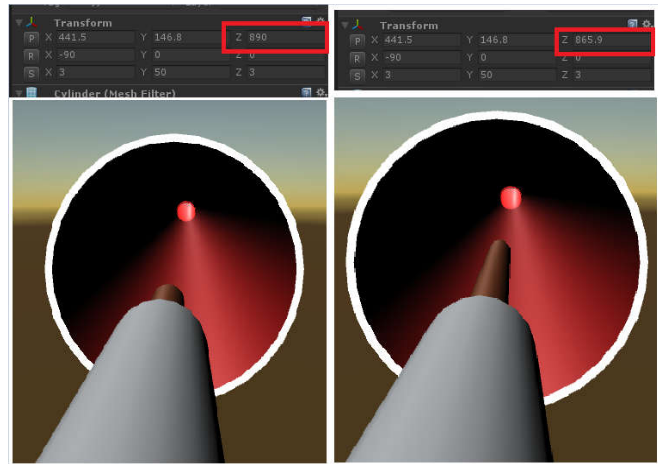

Fig.9 Insertion distance measuring method

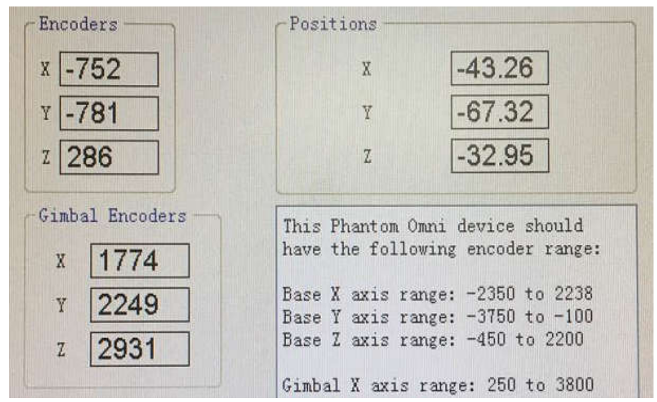

Fig.10 Phantom Omni displacement recording

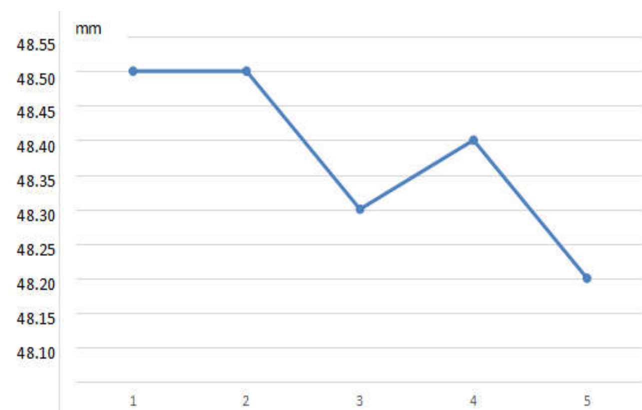

Fig.11 Average insertion in VR system per 5mm displacement of Phantom Omni for 10 seconds

not import to the computer on time, another problem is the vibration of the hand, causing the displacement of the Phantom Omni device not steady, the data that transport to the computer get some error and the insertion distance get the error.

To evaluate the Phantom Omni's accuracy, we build up another program to test when the Phantom Omni device get the displacement, how much the resistance force device gives. As the method above, the more distance Phantom Omni device

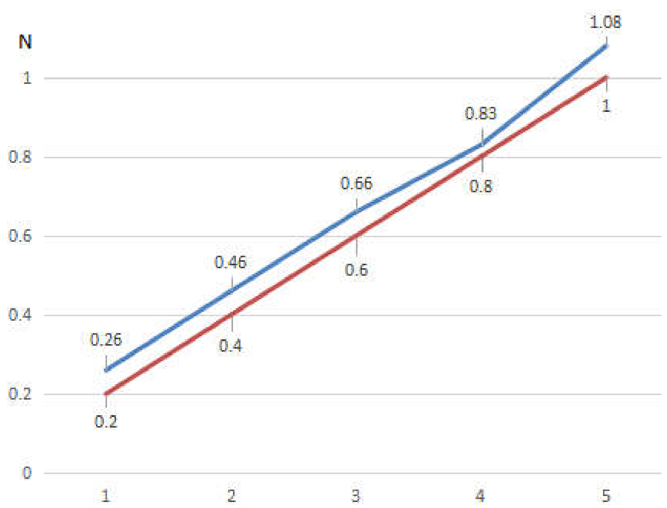

Fig.12 Resistance force Phantom Omni gives

get, the more resistance force Phantom Omni gives, the resistance force are given below.

In this figure, blue line is the resistance force Phantom Omni gives in real, red line is purposed force the device should give. We can find that there's also some errors during the experience, the error is about 0.06N, this problem is due to the Phantom Omni's motor's problem. The experience got a basic success.

IV. Conclusion

In this paper, a VR-based training system is realized which not only provides visualization but also haptic force for trainee. The visualization in VR simulator displays the virtual catheter moving procedure in the vessels as well as real blood vessel. Meanwhile to foster the hand-eye coordination, the Phantom Omni device will apply resistance on catheter. To do the preliminary evaluation, we have analyzed force and displacement in VR for surgery safety. From the catheter navigation and force evaluation, the error could hold in about 10%. Future work is to add some functions in the VR model, such as rotation, collision warning, and import DICOM images into the VR system to get patients' blood vessel model.

Acknowledgement

This research is partly supported by National Natural Science Foundation of China (61375094), National High Tech. Research and Development Program of China (No.2015AA043202).

References

[1] Saliba W, Cummings J E, Oh S, "Novel robotic catheter remote control system: feasibility and safety of trans-septal puncture and endocardial catheter navigation", J cardiovascular electrophysiology, vol. 17, no. 10, pp. 1102-1105, 2006.

[2] Saliba W, Reddy VY, Wazni O, et al., "Atrial fibrillation ablation using a robotic catheter remote control system – initial human experience and long-term follow-up results", J Am Coll Cardiol, vol. 51, pp. 1102-1105, 2008.

[3] Khan E M, Frumkin W, Ng G A, "First experience with a novel robotic remote catheter system: Amigo™ mapping trial", J Interventional Cardiac Electrophysiology, vol. 37, no.2, pp.121-129, 2013.

[4] Arai F, Fujimura R, Fukuda T, "New catheter driving method using linear stepping mechanism for intravascular neurosurgery. Proceedings of IEEE International Conference on Robotics and Automation, 2002. vol.3, pp.2944-2949, USA, 2002.

[5] Thakur Y, Bax J S, Holdsworth D W, "Design and performance evaluation of a remote catheter navigation system", IEEE Transactions on Biomedical Engineering, vol.56, no.7, pp.1901-1908, 2009.

[6] Guo J, Guo S, Xiao N, "A novel robotic catheter system with force and visual feedback for vascular interventional surgery", Int J of Mechatronics and Automation, vol.2, no.1, pp.15-24, 2012.

[7] Xiao N, Shi L, Gao B, "Clamping force evaluation for a robotic catheter navigation system", J of Neuroscience and Biomedical Engineering, vol.1, no.2, pp.141-145, 2013.

[8] Yin X, Guo S, Wang Y, "Force model-based haptic master console design for teleoperated minimally invasive surgery application", Proceedings of 2015 IEEE International Conference on Mechatronics and Automation, pp.749-754, China, 2015.

[9] Tsujita T, Sase K, Konno A, "Design and evaluation of an encountered-type haptic interface using MR fluid for surgical simulators", J of Advanced Robotics, vol.27, no.7, pp.525-540, 2013.

[10] Yin X, Guo S, Hirata H, "Design and experimental evaluation of a teleoperated haptic robot–assisted catheter operating system", J of Intelligent Material Systems and Structures, vol.27, no.1, pp.3-16, 2014.

[11] Ye X, Zhang J, Li P, et al. A fast and stable vascular deformation scheme for interventional surgery training system[J]. Biomedical engineering online, vol.15, no.1, pp.35, 2016.

[12] Guo J, Yu Y, Guo S, et al. "Design and performance evaluation of a novel master manipulator for the robot-assist catheter system", Proceeding of Mechatronics and Automation (ICMA), 2016 IEEE International Conference on. IEEE, pp.937-942, 2016.

[13] Zhou C, Xie L, Shen X, "Cardiovascular - interventional - surgery virtual training platform and its preliminary evaluation", Int J of Medical Robotics and Computer Assisted Surgery, vol.11, no.3, pp.375-387, 2014,

[14] Meng C, Zhang J, Liu D, "A remote - controlled vascular interventional robot: system structure and image guidance", Int J of Medical Robotics and Computer Assisted Surgery, vol.9, no.2, pp.230-239, 2013.

[15] Wu X, Luboz V, Krissian K, "Segmentation and reconstruction of vascular structures for 3D real-time simulation", J of Medical image analysis, vol.15, no.1, pp.22-34, 2011.

[16] Chen P, Barner K E, Steiner K V, "A displacement driven real-time deformable model for haptic surgery simulation", Proceedings of 14th IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp.499-505, 2006.

[17] Cui X Y, Liu G R, Li G Y, "Analysis of elastic–plastic problems using edge-based smoothed finite element method", Int J of Pressure Vessels and Piping, vol.86, no.10, pp.711-718, 2009.

[18] Lloyd B, Székely G, Harders M, "Identification of spring parameters for deformable object simulation", IEEE Transactions on Visualization and Computer Graphics, vol.13, no.5, pp.1081-1094, 2007.

[19] Natsupakpong S, Çavuşoğlu M C, "Determination of elasticity parameters in lumped element (mass-spring) models of deformable objects", J of Graphical Models, vol.72, no.6, pp.61-73, 2010.

[20] Tang W, Lagadec P, Gould D, "A realistic elastic rod model for real-time simulation of minimally invasive vascular interventions", J of The Visual Computer, vol.26, no.9, pp.1157-1165, 2010.

[21] Tang W, Wan T R, Gould D, "A stable and real-time nonlinear elastic approach to simulating guidewire and catheter insertions based on cosserat rod", IEEE Transactions on Biomedical Engineering, vol.59, no.8, pp.2211-2218, 2012.

[22] Wang Y, Guo S, Gao B. "Vascular elasticity determined mass–spring model for virtual reality simulators", Int J of Mechatronics and Automation, vol.5, no.1, pp.1-10, 2015.

[23] Wang Y, Guo S, Tamiya T, "A Blood Vessel Deformation Model Based Virtual-reality Simulator for the Robotic Catheter Operating System", Neuroscience and Biomedical Engineering, vol.2, no.3, pp.126-131, 2014.