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Development of Virtual-Reality Simulator System for Minimally Invasive Surgery (MIS) Using Fractional-Order Vascular Access

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***Abstract*—Currently, minimally invasive surgery (MIS) is applied in the diagnosis and surgery using an endoscope or a catheter for neurosurgery and for endovascular diseases, such as aneurysm, atrial septal defect (ASD), embolization, and cerebral aneurysm. This study proposes virtual-reality (VR) simulator system for double interventional cardiac catheterization (ICC) using fractional order vascular access tracker and haptic force producer. An endoscope or a catheter for diagnosis and surgery of cardiovascular disease has been commonly used in minimally invasive surgery. It needs specific skills and experiences for young surgeons or postgraduate year (PGY) students to operate a Berman catheter and a pigtail catheter in the inside of the human body and requires avoiding damaging vessels. To improve the training in inserting catheters, a double-catheter mechanism is designed for the ICC procedures. A fractional-order vascular access tracker is used to trace the senior surgeons' consoled trajectories and transmit the frictional feedback and visual feedback during the insertion of catheters. Based on the clinical feeling through the aortic arch, vein into the ventricle, or tortuous blood vessels, haptic force producer is used to mock the elasticity of the vessel wall using voice coil motors (VCMs). The VR establishment with surgeons' consoled vessel trajectories and hand feeling is achieved, and the experimental results show the effectiveness for the double ICC procedures.**

Keywords—minimally invasive surgery (MIS); virtual-reality (VR); interventional cardiac catheterization (ICC)

I. Introduction

In recent years, with the development of cardiovascular interventional procedure, atrial septal defect (ASD) surgery has become the main way to treat type II ASD [1]. The advantages of cardiovascular interventional procedure are: reduce the possibility of infection, general anesthesia and the time of being in hospital. However, two-dimensional X-ray images provided in the procedure could not provide surgeons the actual structure of heart and precise three-dimensional position of the defect, so it's not so easy for a new physician to perform. In general, new doctors is led by a senior physician for procedure training, but this approach has some potential dangers, therefore, this study will design a computer simulation of double-catheter training system for atrial septal defect that provides physician a platform to practice and be familiar with the operation of various processes, including learning how to manipulate the catheter to the correct position for diagnosis and treatment.

The system provides the user interface including the records of the operating parameters such as the exerted force on the catheter, the displacement and rotation angle of the double catheter, the processing time required to complete a treatment…etc. In addition, the system can be set or provide the real situation which may be encountered while doing simulations of the treatment, for example, the operating skills of passing through the specific location, if the users accidentally bump into the vessel wall, the simulating training system will generate reverse thrust force to the users so that it can make the simulation more realistic and achieve the training outcomes. In the future, we expected that the system can be applied as a teaching platform in hospital that allows users to practice repeatedly to achieve proficiency results and finally improve the success rate of treatment.

II. System Description/ Methods

A. Virtual-Reality (VR) Simulator System

A VR simulator is the use of visual feedback and an e-learning environment to create, impart, practice, and check senior surgeons' experiences using interactive scenarios to reflect surgery situations. Some e-learning instructions include the contrast medium injection, angioplasty operation, graft-stent implantation, and fluoroscopy (iodine-based contrast) with digital subtraction angiography. After instructions, young surgeons or PGY students need about 30min to complete the guidewire manipulation and fluoroscopy examinations. In ASD surgery, it is important to enhance the safety operation, while avoiding damaging the blood vessel, such as aortic arch and right femoral vein into the ventricle. Therefore, establishing the force and visual feedback between a catheter and vessel wall is the main issue in this study. Based on the clinical feeling, the proposed VR simulator system comprises three functional components that include hardware mechanism, the mechanism of double ICC is shown in Figure 1, which consists of haptic force and friction force producer for force feedback, rotation and displacement detector for visual feedback, and double catheters.

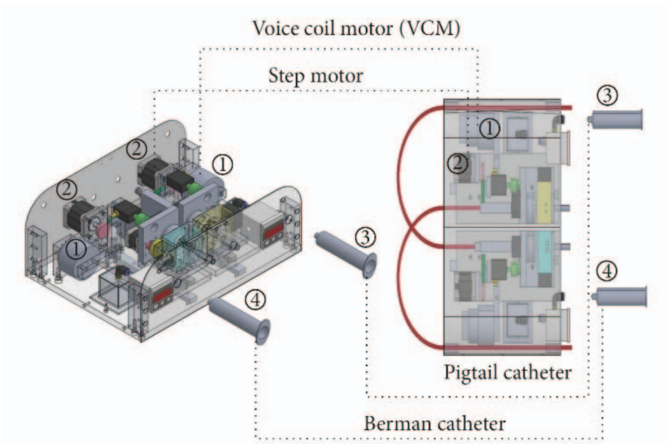

Fig. 1. VR simulator system: haptic force and friction force producer for force feedback

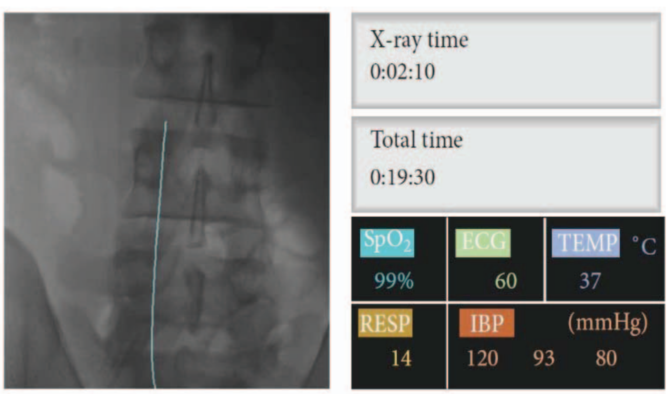

Fig. 2. VR simulator system: human-machine interface

B. Methodology Description

Digital image processing comprises image enhancement process, image binarization, edge detection, and femoral arterial/venous vessel location. By feeding the digital images into the computer, as shown in Figure 3, the image enhancement process is used to modify the gray-scale values using an intensity transformation function to adjust the contrast between certain intensity values [2–6]. Intensity transformation uses a nonlinear mapping function to enhance the image detail of the original image[6]:

$$g(\mathrm{r,c}) = \frac{MK}{\sigma(r,c)}[\mathrm{F}(r,c) - \mathrm{M}(r,c)] \tag{1}$$

where pixel $g(r, c)$ is individually processed, M is the mean of all of the gray-level values, $\sigma(r, c)$ is the gray-level variance of each 3 × 3 detection mask, $M(r, c)$ is the mean gray-level value for each detection mask, and k is a parameter, $0 < k < 1$. Image edges are boundaries between different gradients in an image. For image segmentation, a first-order derivative is used to identify the discontinuities in intensity from one pixel to another.

In order to mock the situation of the intravascular catheter inside a blood vessel, the VR simulator system needs to provide the force feedback to a surgeon/trainer at the corner of the tortuous blood vessel, as shown in Figure 4. We propose an access tracker to locate the specific point, while VR simulator system can produce contact force information between the catheter and the blood vessel. Then, VCM is employed to realize haptic force with the mechanical controller and feeds it back to the operator/ trainer. Therefore, the trajectory tracker, using the self-synchronization error based on nonlinear tracking model, is used to locate the image polar coordinates of tortuous blood vessel.

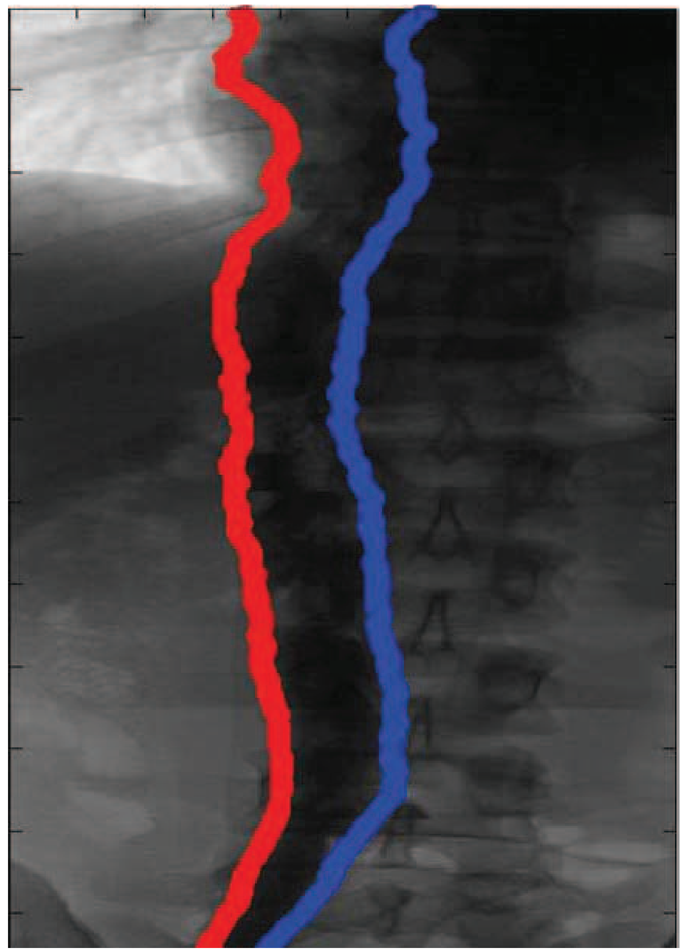

Fig. 3. X-ray image, the frontal view of human body in x-y plane, vessel trajectories as red color and blue color

A Sprott system, which consists of an MS as a reference and an SS, is used to design a fractional-order tracker to track the trajectory of the blood vessel and locate the coordinate point of the tortuous blood vessel, as shown in Figure 5, and its general model is defined elsewhere [7–9]:

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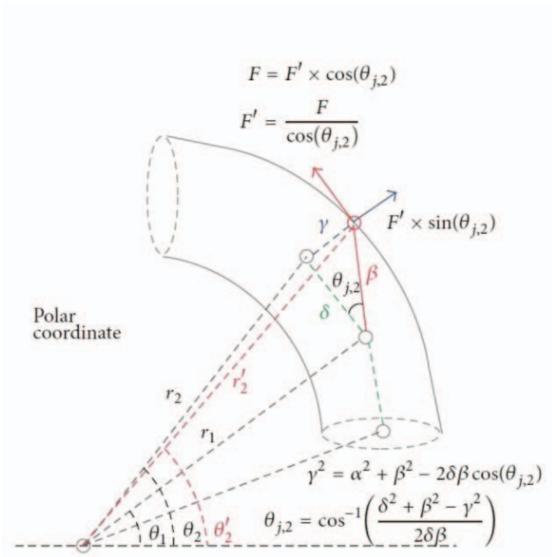

Fig. 4. Image polar coordinates of tortuous blood vessel

$$\begin{bmatrix} \dot{r_{1m}} \\ \dot{r_{2m}} \\ \dot{r_{3m}} \end{bmatrix} = \mathrm{A} \begin{bmatrix} r_{1m} \\ r_{2m} \\ r_{3m} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 2\, sign(r_{1m}) \end{bmatrix},$$

$$\mathrm{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1.2 & -b & -a \end{bmatrix}$$

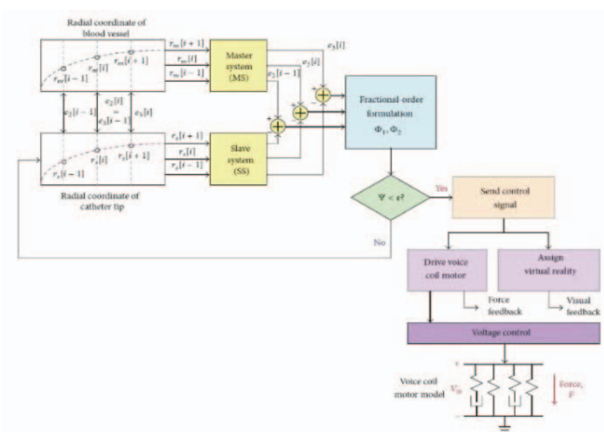

Fig. 5. Fractional-order trajectory tracker and force feedback driver

III. Results and Conclusion

The proposed VR system achieved simulating the ICC procedure using a mechanical design and control. To practice the double-catheter ICC procedures, we have basic and intermediate skills to operate double catheters, such as spatiotemporal location, hand-eye coordinate, and two handed operation at the straightforward and tortuous vascular accesses, including coronary artery, right femoral vein/left femoral artery, and carotid arteries. Advanced skills can be also applied for further applications, including therapies for peripheral vascular disease (PVD), ASD, endovascular grafts tent placement, and neurosurgery. For example, the proposed VR system could be used to mock PVD treatments to reconstruct occluded vessel access or reposition stents. It needs 3D imaging guidance to track vascular structures and force control to perform surgical repairs. Thus, 3D image servo-control and catheter tip sensor can enhance the visual feedback, which can provide the catheter's motion trajectories and the specific sites in the human body. We also expect that the proposed VR simulator system can be applied in surgery education, angioplasty, stenting, catheter-based drug delivery, and clinical training usages; the training purposes can further consider senior surgeons' experiences to make the young surgeons or PGY students highly improve their skills after a series of training and practices.

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