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Development of a 3D blood vessel model for the Simulation of the Minimally Invasive Surgery

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***Abstract* - In this paper, we build one VR system which is used for the training of the interns to operate the Robotic Catheter System and improve the operational experience and auxiliary medical process for the minimally invasive surgery, uses the open source code DCMTK to read the information about DICOM file and carry out the CT image segmentation for the Virtual Reality based Robotic Catheter System. In order to get the vessel model, apply Open Scene Graph (OSG) to realize the 3D image output and catheter control of the Virtual Reality System, according to the 4 area method, blood vessel data can get from the text file,. Finally, the vessel model is used in the VR simulator for training surgery and the system is fit for training unskilled surgeons to do the operation of intravascular neurosurgery.**

Index Terms – minimally invasive surgery, DCMTK, virtual reality simulators,

I. INTRODUCTION

MIS technique is used to reduce trauma to healthy tissue since this trauma is the leading cause of patient post-operative pain and prolonged hospital stay. Less hospital stay and rest periods also reduce the cost of surgery and are among other advantages of this method. However, a critical disadvantage of this surgery technique is its complexity, requiring a high training effort of the surgeon because the arteries through which the catheter passes are extremely complex and delicate. The repeated insertion of the catheter through several trials could tear a blood vessel at a junction and cause bleeding and excessive pressure could rupture the blood vessels. For practical and ethical reasons, realistic virtual reality simulators provides the most powerful aids compared to the other available alternatives such as anesthetized animals, human cadavers and patients. The VR simulators enable novice doctors to learn basic wire or catheter handling skills and provide the expert practitioners the opportunities to rehearse new operating procedures prior to performing on the patient.

One of the most popular products have been developed is a robotic catheter placement system called Sensei Robotic Catheter System [1-3] offered by Hansen Medical. The Sensei provides the physician with more stability and more force in catheter placement with the Artisan sheath compared to manual techniques, allowing for more precise manipulation with less radiation exposure to the doctor, commensurate with higher procedural complications for the patient. Because of the sheath's multiple degrees of freedom, force detection at the distal tip is very hard. Catheter Robotics Inc. has developed a remote catheter system called Amigo. This system has a robotic sheath to steer catheters which is controlled at a nearby work station, in a manner similar to the Sensei system. The first in human use of this system was in April 2010 in Leicester UK, where it was used to ablate artificial flutter [4]. Magnatecs Inc. has produce their 'Catheter Guidance Control and Imaging' system. This has 4 large magnets placed around the table, with customized catheters containing magnets in the tip. The catheter is again moved by the magnetic fields and is controlled at a nearby work station. The system facilitates precise vector based navigation of magnetically-enabled guide wires for percutaneous coronary intervention (PCI) by using two permanent magnets located on opposite sides of the table to produce a controllable magnetic field.

Because minimally invasive techniques have unavoidable reduced the sense of touch compared to open surgery, surgeons have to rely more on the haptic feeling generated by the interaction between blood vessels and the catheter. Even if the color and texture of blood vessels convey crucial anatomical information visually, touch is still critical in the surgeries. The benefits of using haptic feedback devices in minimally invasive surgery training through simulation have already been recognized by several research groups and many of companies working in this area [1-11]. However, in these researches, the virtual surgical training was carried out without haptic feedback, or researched on the virtual model of body organ not the vascular physical model. Moreover, some achievements in this area used Phantom Omni or other haptic devices as a controller to operate the virtual minimally invasive surgery [12-13]. Nevertheless, it is not convenient when surgeon drive the catheter for inserting and rotating because it does not accord with the custom of surgeons' operations.

In this paper, we prepare to develop a Virtual Reality based Robotic Catheter System, including the design of the Catheter Operating System, 3D Image Generation, Information Interaction and Mechanics Model analysis, and at last we will set up the VR system to simulate the process of inserting the catheter. And present the virtual reality simulators based on a novel robotic catheter operating system for surgeons' training in minimally invasive surgery.

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II. THE VR BASED ROBOTIC CATHETER SYSTEM

The structure of the Virtual Reality based Robotic Catheter System which could be used in operation training and remote catheter control, as shown in Fig. 1 and Fig. 2. And the User interface of 3D vessels in a VR system shows the information of the 3D vessel, as shown in Fig. 3. In the master side, the surgeon operates the handle to drive the catheter for inserting and rotating to clamp catheter directly, the control commands of the catheter operating system were transmitted to the slave side, after the slave side PC receiving the control commands from master side, the mechanism clamps the catheter to insert and rotate inside the blood vessel and at the same time simulate the surgeon's operating skill. The load cell was used for detecting the frictional force between catheter and blood vessel, the torque sensor and motor were used for detecting rotating information of the catheter, and could be transmitted to the surgeon's hand in master side. Then the surgeon can decide whether inserting or rotating the catheter depending on the feedback information and the visual information.

On the slave side, the catheter manipulator is as well as the controller, it means that the catheter manipulator could keep the same motion with the operator's hand. The operation will become visualized and easy to begin. On the other hand, this structure can realize the mechanical feedback to the surgeon. This part is placed in the patient side. The catheter is inserted by using this mechanism. This part contains two DOFs, one is axial movement alone the frame, and the other one is radial movement. Two grapes are placed on this part. The surgeon can drive the catheter to move along both axial and radial when the catheter is clamped by front grasped. The catheter keeps its position and the catheter driven part can move freely when the catheter is clamped by second grasper. During the operation of intravascular neurosurgery, it is significant to obtain the contact force information between catheter and blood vessel.

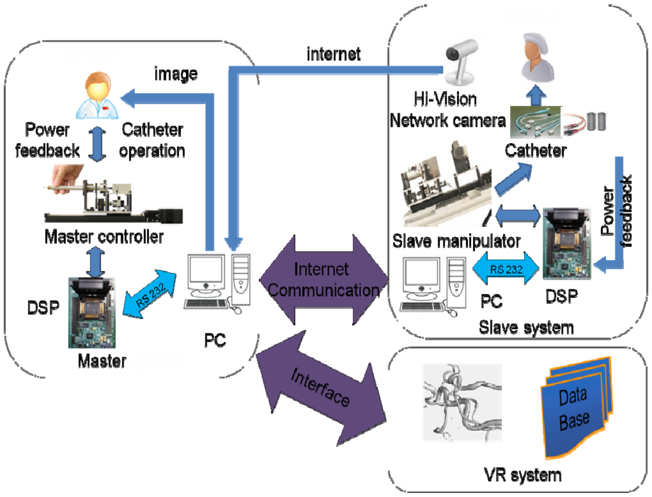


Fig. 1 the Structure of the Virtual Reality based Robotic Catheter System

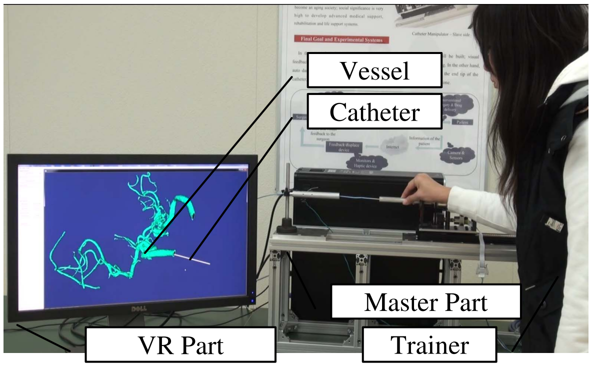


Fig. 2 Virtual Reality based Robotic Catheter System

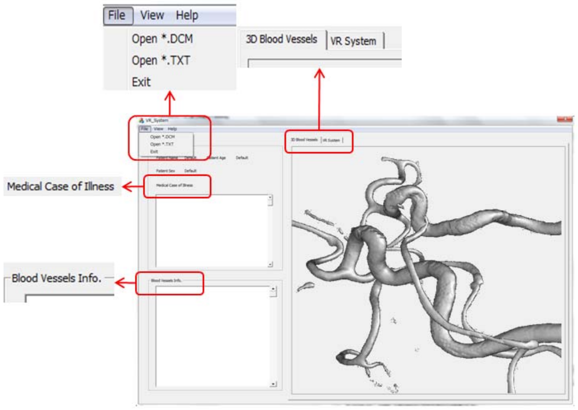


Fig. 3 User interface of 3D vessels in VR system

III. 3D BLOOD VESSEL MODEL

We have used DCMTK to read the information from the DICOM file. X-ray computed tomography (CT) is a medical imaging method employing tomography created by computer processing. Digital geometry processing is used to generate a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation.

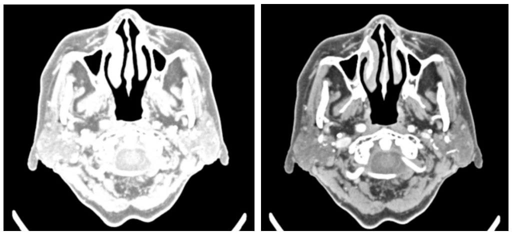
We use the software Cmake to install the DCMTK to the VC++ package. We need install "DCMTK 3.5.4-source code packages", "DCMTK 3.5.4-support libraries for windows", "Cmake 2.8.4 (one of Packages compiled tools)". Then we can use DCMTK to complete the image segmentation. Image gray value calculation formula can be shown in the equation (1). According to the CT value of the DICOM file which can present different parts of the human body, it is possible for us to change the gray value in the program and realize image segmentation.

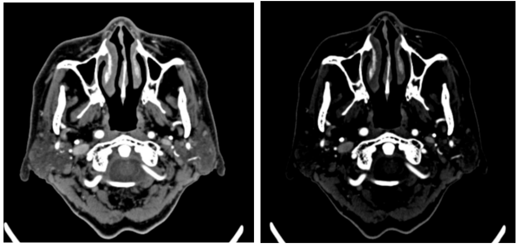
$$G(V)=\begin{cases} 0, & V<C-\dfrac{W}{2} \\ \dfrac{g_m}{W}\left(V+\dfrac{W}{2}-C\right), & C-\dfrac{W}{2}\le V\le C+\dfrac{W}{2} \\ g_m & V>C+\dfrac{W}{2} \end{cases} \tag{1}$$

where, V means image data, G(v) means Value displayed,

g_m is the maximum value displayed, W is the display window wide, C is the window level.

As shown in Fig. 4, we use Windows-Leveling method gets the 2D image. We can adjust the value of the window and leveling to divide the vessel from the image. As shown in Fig. 5, all vessels could be shown in each picture, and we can get the center coordinates and save into ".txt" file. After that, we use four area method to find the edge of the vessel point in Fig. 6, then draw the vascular section after segmentation as shown in Fig. 7 (a) and vascular surface as shown in Fig. 7 (b).


(a) W=1800 L=-500 (b) W=1500 L=-200


(c) W=1100 L=200 (d) W=1100 L=400

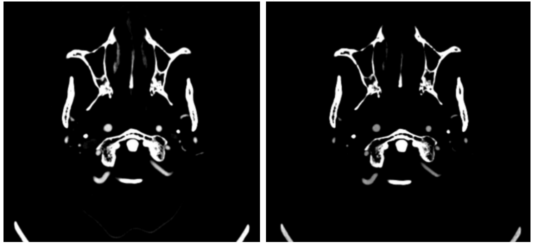

(e) W=500 L=200 (f) W=500 L=400

Fig. 4 2D image by W-L method

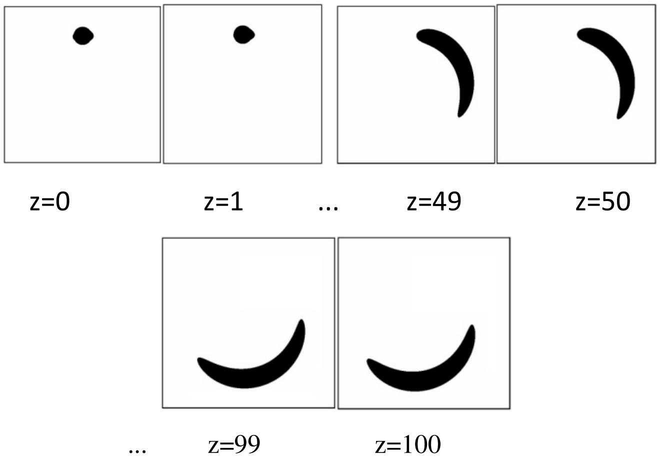


Fig. 5 Vessel points in 2D image

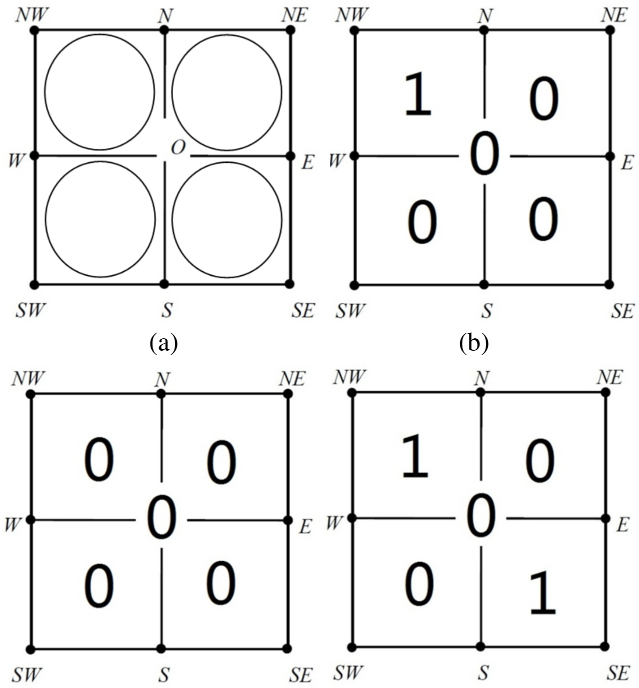


Fig. 6 the edge of the vessel point


(a) (b)

Fig. 7 the Vascular section after segmentation

It is necessary to use coordinate transformation, when we draw the 3D model of the vessel. The linear transformation matrix as shown in follows:

$$\Delta = \begin{bmatrix} eM11 & eM12 & eM13 & 0 \\ eM21 & eM22 & eM23 & 0 \\ eM31 & eM32 & eM33 & 0 \\ eDx & eDy & eDz & 1 \end{bmatrix} \quad (2)$$

$$X' = eM11 \times x + eM12 \times y + eM13 \times z + eDx \quad (3)$$

$$Y' = eM21 \times x + eM22 \times y + eM23 \times z + eDy \quad (4)$$

$$Z' = eM31 \times x + eM32 \times y + eM33 \times z + eDz \quad (5)$$

Parallel translation conversion results as shown in Fig. 8 and rotation conversion as shown in Fig. 9. Arbitrary axis rotation conversion as shown in Fig. 10.

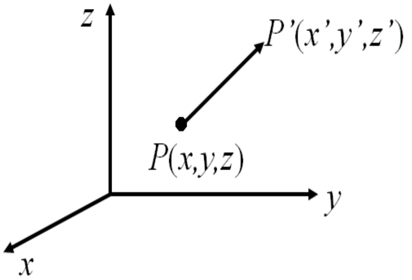
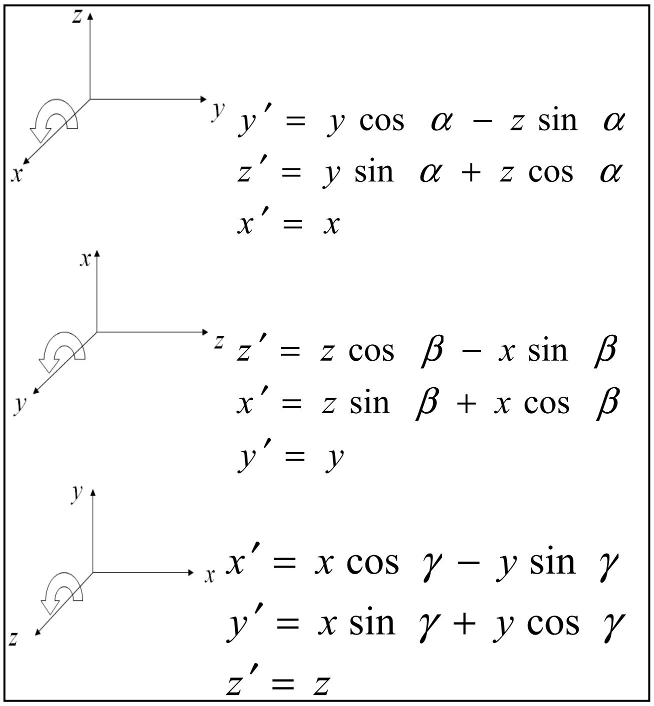


Fig. 8 Parallel translation conversion

$$(x'\,y'\,z'\,1)=(x\,y\,z\,1)\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\t_x&t_y&t_z&1\end{bmatrix}\quad\begin{cases}x'=x+t_x\\y'=y+t_y\\z'=z+t_z\end{cases}\tag{6}$$



$$y' = y\cos\alpha - z\sin\alpha$$
$$z' = y\sin\alpha + z\cos\alpha$$
$$x' = x$$

$$z' = z\cos\beta - x\sin\beta$$
$$x' = z\sin\beta + x\cos\beta$$
$$y' = y$$

$$x' = x\cos\gamma - y\sin\gamma$$
$$y' = x\sin\gamma + y\cos\gamma$$
$$z' = z$$

Fig. 9 Rotation conversion

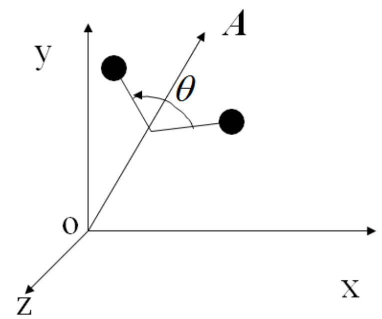


Fig. 10 Arbitrary axis rotation conversion

$$\hat{A}=\begin{bmatrix}a_xa_x&a_xa_y&a_xa_z\\a_ya_x&a_ya_y&a_ya_z\\a_za_x&a_za_y&a_za_z\end{bmatrix}\qquad A^*=\begin{bmatrix}0&-a_z&a_y\\a_z&0&-a_x\\-a_y&a_x&0\end{bmatrix}\tag{7}$$

$$M=\hat{A}+(I-\hat{A})\cos\theta+A^*\sin\theta\tag{8}$$
$$P'=P\times M^T$$

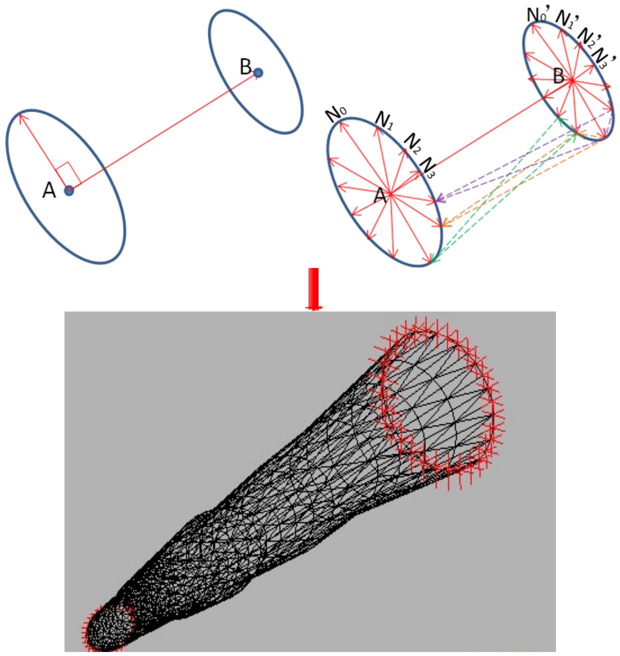


Fig. 11 Coordinate conversion of the vascular section 3D model

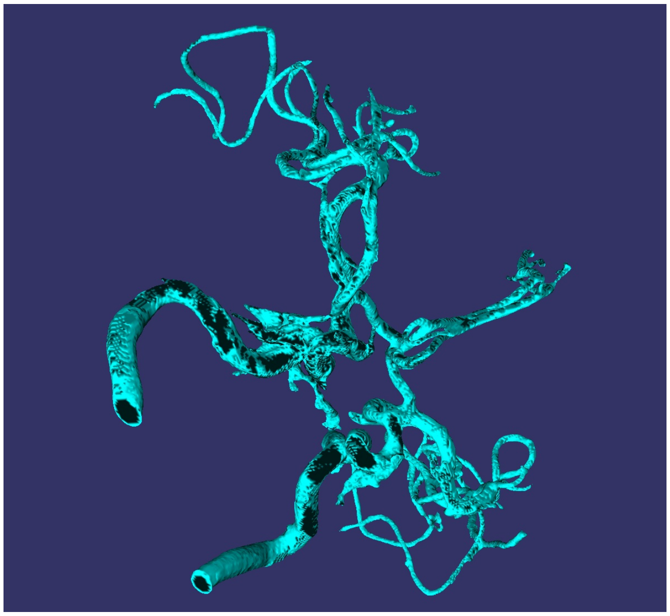


Fig. 12 3D reconstruction images of the blood vessels by OSG

Volume rendering methods generate images of a 3D volumetric data set without explicitly extracting geometric surfaces from the data. These techniques use an optical model to map data values to optical properties, such as color and opacity. During rendering, optical properties are accumulated along each viewing ray to form an image of the data. We use texture mapping to apply images, or textures, to geometric objects. Volume aligned texturing produces images of reasonable quality, though there is often a noticeable transition when the volume is rotated.

The three-dimension reconstruction images of the blood vessels have been shown in Fig. 12, for the multi-branched blood vessels and we can choose a part of them as a research topic.

IV. EXPERIMENTAL RESULTS

When using the Virtual Reality based Robotic Catheter System. The trainer should watch the monitor image and operates the handle of master manipulator to insert or rotate catheter, as operate the catheter directly, at the same time, the controlling instructions are transmitted to the virtual reality environment. The catheter in a virtual reality environment can insert or rotate catheter according to the controlling instructions from master side. If the catheter contacts the blood vessel, the force feedback can be detected, stored and transmitted to the surgeon’s hand. Based on the force feedback and monitoring image information, the virtual reality environment can be used for medical training.

Fig. 13 show us the Simulation of catheter inserting into the 3D vessel model. We should calibrate the position of the catheter in the 3D vessel model, and make the master side consist with the VR side, as shown in Fig. 14 and Fig. 15, we can see the displacement error of the catheter is small, so that, we can say that the system is suitable for the training, and the vessel model can be used in the training simulation of the operation.

IV. CONCLUSIONS

In this paper, we introduced a kind of Catheter Virtual Reality System which is used for the training of the interns to operate the Robotic Catheter System and improve the operational experience and auxiliary medical process. The open source code DCMTK toolkit was used to read the information of DICOM file and carry out the CT image segmentation for the Virtual Reality based Robotic Catheter System. Then, we use Open Scene Graph (OSG) to realize the 3D image output of the skill. The characteristic evaluations (rotating motion and inserting motion) have also been done to verify the validity of the system, the experimental results indicated that the stability and responsibility of system were good, the robotic catheter system was fitting to be used for training unskilled surgeons to do the operation of intravascular neurosurgery.

In the future works, we will use the Virtual Reality System to help the unskilled surgeon improve their experience and make sure the safety of the operation by using the robotic catheter system.

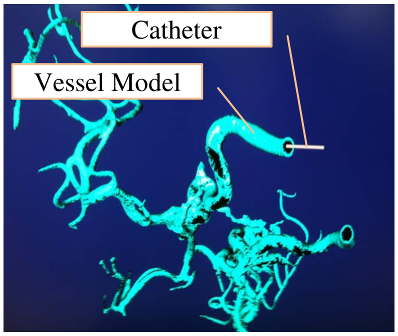


Fig. 13 Simulation of catheter inserting into the vessel model.

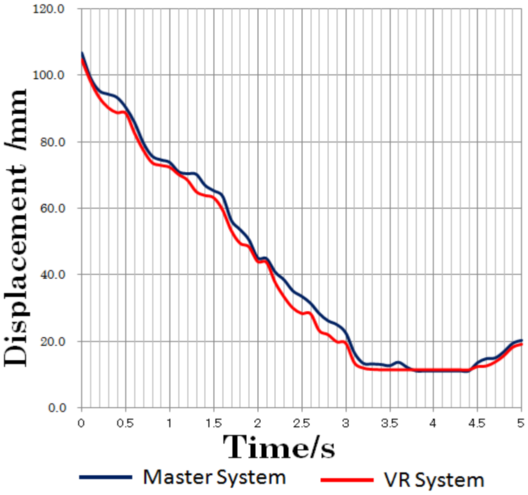


Fig. 14 Backward control of the catheter

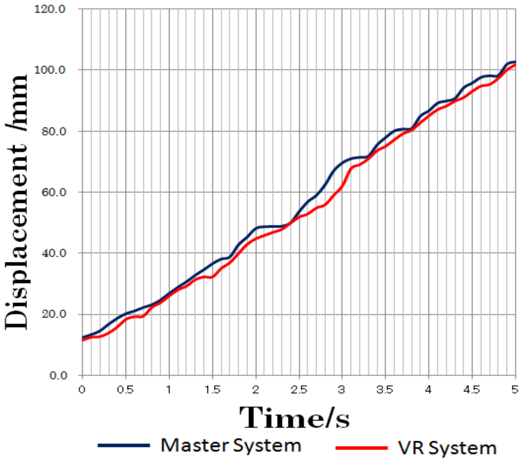


Fig. 15 Forward control of the catheter

Acknowledgements

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