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A Haptic Interface Design for a VR-based Unskilled Doctor Training System in Vascular Interventional Surgery

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***Abstract* – Vascular Interventional Surgery (VIS) is a minimally invasive surgery technique (MIS) where guidewires and catheters are steered in the vascular system under X-ray imaging. In order to perform these procedures, a radiologist has to be correctly trained to master hand-eye coordination, instrument manipulation and procedure protocols. A tele-operative robotic catheter master system was designed for vascular interventional surgery, to reduce radiation-exposure times, and afford unskilled surgeons the opportunity to learn basic catheter/guidewire skills, while allowing experienced physicians to perform surgeries cooperatively. This paper focuses on the requirements, design and prototyping of the haptic device and the translational and rotational measurement part dedicated to catheters. Two cameras are used to track the translational and rotational displacements of the catheter in real time for the contactless measurement and four permanent magnets and coils are applied to generate the Ampere force in order to realize the haptic feedback. During the training process, novice doctors can drive the real catheter directly and carry out the intervention with haptic interfaces with force feedback, which provides the surgeon with a sense of touch. Additionally, the proposed master system can be used as the controller for not only the virtual reality training system but also the catheter manipulator of a slave system.**

Index Terms* – *Vascular Interventional Surgery (VIS), master system, haptic device, translational and rotational measurement

I. INTRODUCTION

Vascular interventional surgery (VIS) is a minimally invasive therapy for treatment of arterial aneurysm and other vascular disease [1]. During this surgical procedure, surgeons direct a catheter/guidewire inside the patient's vascular structure, from the femoral artery to the target position, to cure the vascular disease by manipulating the tail part of the catheter. The main advantages of this surgical method include a smaller incision, decreased postoperative pain, less blood loss and a quicker recovery [2]. However, because the vascular structure through which the catheter passes is highly intricate and delicate, VIS requires extensive training by the surgeon to achieve competency. The reduplicative insertion of the catheter through several tests could tear a blood vessel at some region and cause bleeding instantaneously and excessive pressure could crack the blood vessels. For practical and ethical reasons, realistic virtual reality simulators provides a promising alternative method compared to 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 without any damage to both patients and surgeons. The benefits of using simulators in minimally invasive surgery training have already been recognized by several research groups and many of companies are working in this area [3]-[5].

Most importantly, the controller for the virtual reality training system directly impact on the training effect of unskilled doctors. Because minimally invasive techniques has 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 colour and texture of blood vessels convey crucial anatomical information visually, touch is still critical in the surgeries.

A lot of products and researches are reported in this area. One of the popular products is a robotic catheter placement system called Sensei Robotic Catheter System supplied by Hansen Medical [6]-[7]. The Sensei system provides the physician with more stability and more force in catheter placement with the Artisan sheath compared to manual techniques, allows for more precise manipulation with less radiation exposure to the doctor, and is commensurate with higher procedural complications to the patient. Because of the sheath's multiple degrees of freedom, it is very hard to realize the haptic feedback at the controller part. Catheter Robotics Inc. has developed a remote catheter system called Amigo [8]. This system has a robotic sheath to steer catheter which is controlled at a nearby work station, in a manner similar to the Sensei system. The first human trail of this system was in April 2010 in Leicester UK, where it was used to ablate atrial flutter. Yogesh Thakur et al. [9] developed a kind of remote catheter navigation system. This system allowed the user to operate a catheter manipular with a real catheter. So surgeon's operative skills could be applied in this case. The disadvantage of this system is lack of mechanical feedback. T. Fukuda et al. [10] at Nagoya University proposed a custom linear stepping mechanism, which simulates the surgeon's hand movement. Regarding these products and researches, most concerns are still the safety. Force feedback of the catheter during the operation is very important to ensure the safety of the surgery.

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However, display of the force feedback on the controller is very hard to solve in these systems. A potential problem with a remote catheter control system is the lack of mechanical feedback that one would receive from manually controlling a catheter. Moreover, some achievements in this area used Phantom Omni or other haptic devices as a controller to operate the virtual minimally invasive surgery [11-12]. 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 the past, our research group has developed several robotic master systems for the purpose of training unskilled surgeons, which takes advantages of good operability and precision. **Figure 2** shows the general structure of our novel robotic catheter operating system [13]-[19]. The master system has two degrees of freedom. Additionally, a remote animal experiment between Beijing Hospital and Takamatsu was carried out based on the novel robotic catheter operating system. It can simulate the doctors' operation mode in a real surgery but surgeons have to drive the probe part to do the training course. The surgeons cannot pull or push the real catheter directly thereby leading to the bad training effect. In order to allow surgeons to operate on the real catheter directly, the master training system shown in **Figure 3** was proposed [20]. **Figure 3** shows an electromechanical device that measures the axial and radial motion of the input and output catheter using two mechanically independent passive sensors. Each sensor contains a 2,000 lines encoder, mechanically coupled to the catheter. Axial position of the catheter is measured using a mechanical structure that converts the axial motion of the catheter to a rotational motion of the shaft of an optical encoder using two rollers which mechanically couple to the catheter. To measure radial motion, the catheter is used as a shaft to be coupled with the radial encoder. A kind of hollow encoder is constructed to house catheter and coupling, which housed one screw. Based on this master system, surgeons can operate on the real catheter directly, however, two rollers will clamp the catheter and it is very difficult to display the haptic information. The main problem of it is the contact measurement for translation and rotation of the catheter. Therefore, in order to realize the contactless measurement, the system shown in **Figure 4** was developed [22].The photoelectric sensor is used to measure the information of displacement and rotation of catheter. It performed well in the translation measurement of the catheter, but it had a low accuracy in the rotation measurement. **Figure 5** shows a simple master system based on an acceleration sensor which is attached to the glove. During the training procedure, surgeons have to wear the glove and the translational and rotational information of the catheter will be calculated by the acceleration sensor. It is freer than the other master systems. But the accuracy of the measure results is not competent [23].

Therefore, the objective of this paper is to present a new master system in which two cameras are used to track the translational and rotational displacements of the catheter in real time for the contactless measurement and four permanent magnets and coils are applied to generate the Ampere force in order to realize the haptic feedback. Additionally, the master system allow novice doctors to simulate surgeon's operating skills to insert and rotate catheter like surgeon operates catheter directly and carry out the intervention with haptic interfaces with force feedback, which provides the surgeon with a sense of touch.

This paper is organized as follows. In Section II, we present the method used to realize the haptic part design of the new master system. In Section III, the translational and rotational measurement mechanism for catheter master operating system is introduced. Finally, a brief conclusion and future work section are presented in Section IV.

II. METHOD AND IMPLEMENTATION

A. Catheterization System

The catheterization system is composed of a master system and a slave system. The master system, as a surgeon's controller, is located at the operation location for the surgeons to operate by pulling/pushing or rotating the catheter; while, the slave system, as a catheter manipulator, is placed at the patient side. The master system has three degrees of freedom and the slave system has two degrees of freedom. The axial and radial movements of the surgeon's hand at the master side can be detected by measuring the axial displacement and the rotation angle of the catheter, and then transmitted to the catheter manipulator at the slave side. The internet-based communication between the controller and the catheter manipulator will be established.

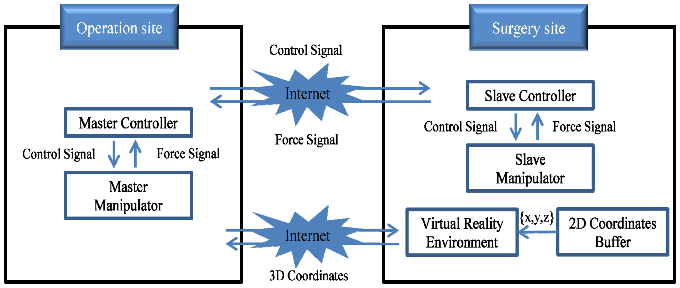


Fig. 1. Structure of the proposed new master system

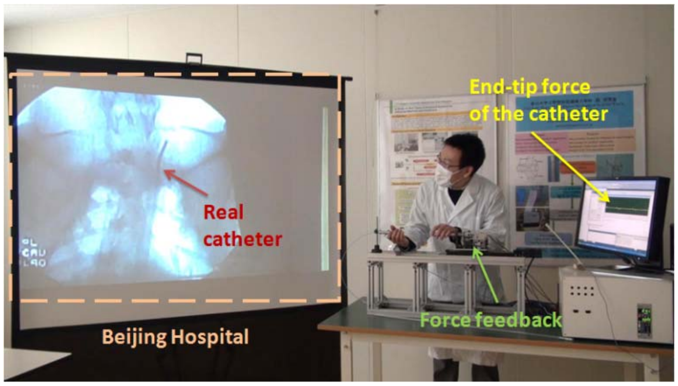


Fig. 2 An animal experiment between Beijing Hospital and Takamatsu

B. General Structure of the Master System

The surgeon’s controller is the master side of the whole system, as shown in **Figure 6**. This system is mainly consisted of three parts, including the hollow cylinder with two slide ways, a stand with one degree of freedom and the force feedback generation section for applying force feedback to the operation section. With the one-degree-of-freedom stand, surgeons can choose a variety of directions to insert the catheter for adapting to various complex operations.

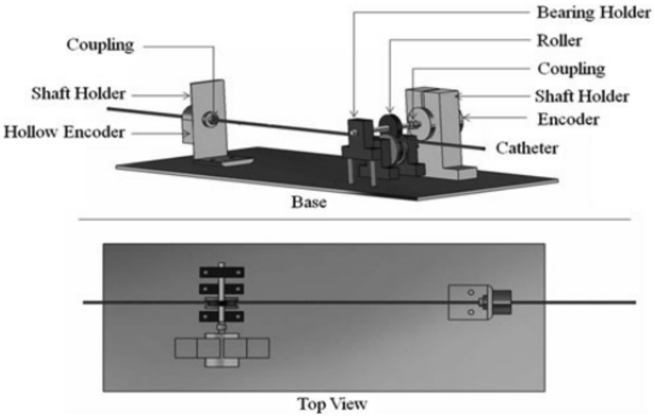


Fig. 3 A master system for doctor training

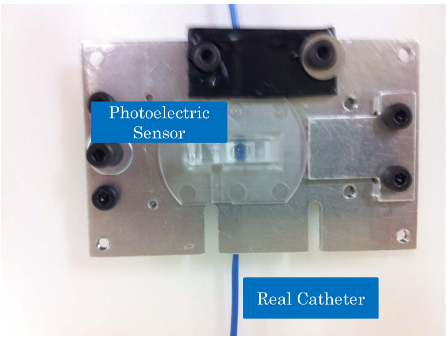


Fig. 4 A master system based on an optical sensor

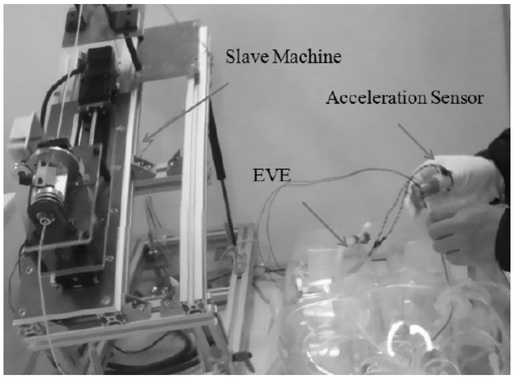


Fig. 5 A master system based on an acceleration sensor

Figure 8 shows the structure of the force feedback generation section. The force feedback generation section, main part of this system, is composed of an electromagnetic flat coil actuator and a bearing with a clamp, both of which are incorporated into the movement stage moving on the slide ways, and four permanent magnets anchored on the movement stage of a screw bearing actuated by a stepping motor. During the operation, the surgeons insert the catheter through an open clamp carried on the center of the bearing incorporated into the movement stage moving on the slide ways. The clamp is driven by a spring and an SMA (Shape Memory Alloy) actuator to be on and off. When the clamp is closed, the catheter will be fixed to the shelf of the electromagnetic flat coil actuator and move on the slide ways. The permanent magnet assemblies including four magnets are controlled to move along the screw bearing by the stepping motor. In order to generate a sustained and steady force feedback, the permanent magnet assemblies will follow the movement of the electromagnetic flat coil actuator to keep their relative position still. In this structure, the axial force feedback will not affect the radial movements.

A switch fixed on the left handle part was used to control the grasper 1 and grasper 2 on the catheter manipulator. Two graspers were used for axial and/or radial displacement. Grasper 1 was used by the surgeon to integrate the catheter with the manipulator. The manipulator can then drive a catheter along both the axial and radial direction. And the axial movement was realized by a movement stage. When the catheter was clamped by Grasper 2, catheter retained its position; however the catheter drive was allowed to move freely. **Figure 7** shows the operating principle of the catheter manipulator of a slave system or a virtual reality training system.

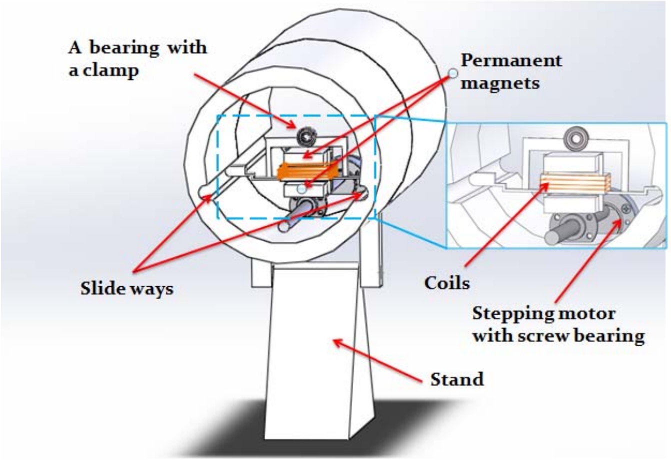


Fig.6. General structure of the master side

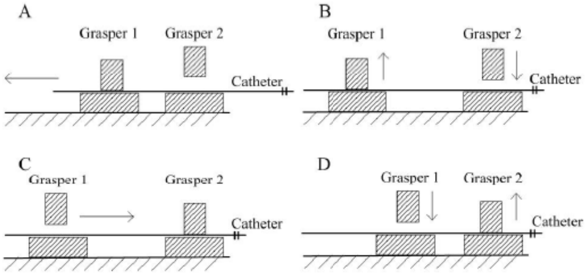


Fig.7. Insertion process.

C. Electromagnetic Actuator

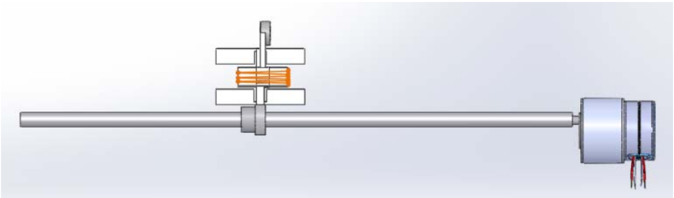
Figure 9 shows the exploded view of the electromagnetic flat coil actuator configuration. When a coil current I flows through the copper coil, it interacts with the magnetic field and produces a force described by

$$F = -I \int_{C} B \times dl \qquad (1)$$

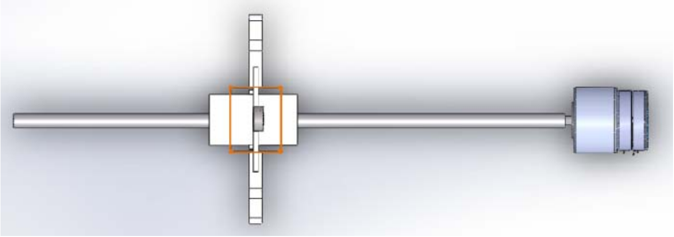
where dl is a differential element of wire in the coil, and the integration is performed over the entire wire. Considering that the field is roughly constant in the magnet gap and negligible elsewhere, the net force on the coil acts linearly along one axis with its orientation decided by the direction of the current.

D. Control System Mechanisms

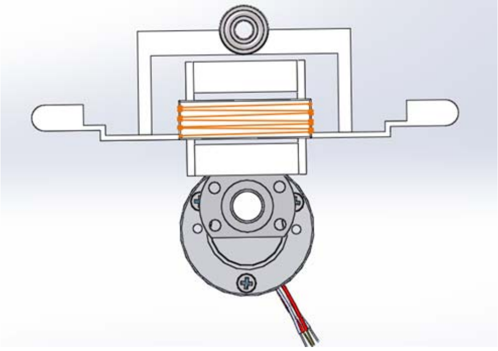
Each of controller side and catheter manipulator side employs a DSP as their control unit. An internet based communication is built between the controller and the catheter manipulator. The controller side sends axial displacement and rotation angle of the handle to the catheter manipulator. At the same time the catheter manipulator sends force information to the controller side. Serial communication is adopted between PC and control unit of the mechanism. The baud rate of the serial is set to 19200.



(a) side view



(b) top view



(c) front view

Fig.8. Force feedback section

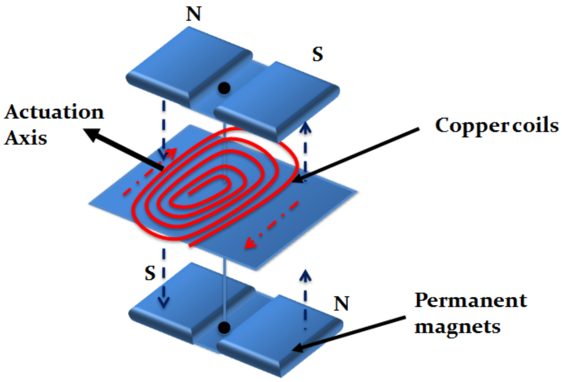


Fig. 9 Exploded view of flat coil actuator configuration

To improve the accuracy of rotation angle and displacement between the catheter manipulator of the slave system and the controller of the master system, dynamic models and control methods (Fuzzy Proportional-Integral-Derivative) were used during remote surgical experiments.

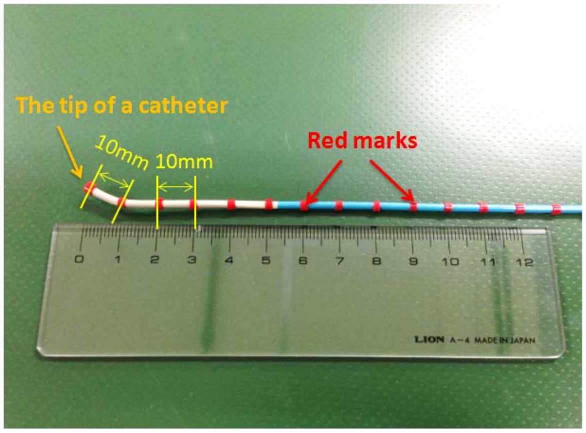


Fig. 10 The red marks attached on a 2mm diameter catheter

III. TRANSLATIONAL AND ROTATIONAL MEASUREMENT

Two cameras are fixed to measure the translational and rotational displacement. Two images are captured at the same time. Then the two images were then fed into a chain of image processing algorithms to calculate the two-dimensional (2-D) coordinates of the feature markers, which were attached to the catheter. These markers were used to represent the catheter shape.

To shorten the image processing time and make it easier to compute the differential value between two features, red instrument markers were attached to a 2-mm-diameter catheter; every two red markers deployed had a 1-cm-spacing. The specific marker distribution is shown in **Figure 10**. The length of a real catheter is ~50 cm; thus, we used 50 red markers to represent the catheter shape. The shape of the catheter inside the pipe was verified by referring to the calculation of the 3-D coordinates for the 50 red markers. Note that the markers were extremely thin, and therefore, did not enlarge the diameter of the real catheter. Additionally, lubricants were used with the catheters in both the real and virtual surgical procedures to decrease frictional resistance.

To recover the 2-D coordinates of each marker on the catheter, we first needed to extract the corresponding feature points (red markers). The feature points from the two cameras were then matched to form identical points, and the disparity between two corresponding feature points was calculated. To identify the red markers in two rectified images, simultaneously captured from the left and right cameras, the images were first converted from red-green-blue (RGB) format to hue-saturation-value (HSV) format. The red markers were then separated from the images by a chain of image processing algorithm; then, lower and upper threshold values were used to extract red markers from the background. Next, an erosion and dilation algorithm was utilized to remove the noise generated by the experimental environment. Finally, circumcircles were calculated for every red marker; the coordinates of the center of each circumcircle were used as its 2-D pixel coordinates.

IV. CONCLUSION AND FUTURE WORK

Based on analysis of requirements and state of the art in computer-assisted training systems for IR, a new hardware haptic interface is proposed. The prototype system offers a realistic behavior, adapts to real or slightly modified instruments, and allows their complete withdrawal. Two cameras are used to track the translational and rotational displacements of the catheter in real time for the contactless measurement and four permanent magnets and coils are applied to generate the Ampere force in order to realize the haptic feedback. Additionally, the master system allow novice doctors to simulate surgeon's operating skills to insert and rotate catheter like surgeon operates catheter directly and carry out the intervention with haptic interfaces with force feedback, which provides the surgeon with a sense of touch.

Further work includes refinement to the current prototype and its control architecture. Test and validation studies of the proposed hardware platform with a variety of simulation software will be carried out by medical partners.

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