Laser Mouse-based Master- Slave Catheter Operating System for Minimally Invasive Surgery
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Abstract – In the minimally invasive surgery, the master and slave system benefits a lot to surgeons for it prevents them from exposure of X-ray radiation. However, for robotic catheter operating master-slave system, it’s important to ensure the synchronization between master and slave sides, which means the catheter motion in slave side following the master side surgeon’s operation. Thus, for above consideration, the position controlled master-slave system is introduced in this paper. To accurately detect the catheter movements in master side, a laser mouse based master device is employed. By laser sensor, the catheter’s position changes can be obtained. Besides, the calibrations have been done for laser sensor to measure the catheter’s insertion and rotation. The results show laser sensor has high accuracy. Finally, to synchronize slave equipment with master side, a PID control strategy is adopted to manipulate two step motors which are responsible for inserting and rotating catheter respectively. The experimental results demonstrate that the PID control method makes the catheter motions in slave side two motors moving closely according to master side.

Index Terms –Minimally invasive surgery, Robotic catheter operating system, Laser sensor, Master and Slave System

I. INTRODUCTION

Since cardiovascular disease and cerebrovascular disease are big risks for mortality in the world, the minimally invasive surgery (MIS) is applied in vascular interventional therapy widely. Because it left small trauma and patients recover fast, the MIS-related products and technology draw much attention both in commercial company and research field. The well-known commercial catheter robotic systems Sensi[1] and Amigo[2] are manufactured by Hansen Medical and Catheter Robotic Inc. The Sensi and Amigo allow physicians to navigate the catheter with greater stability and accurate position. And the physicians used remoter controllers prevent physicians from exposure to the radiation field. But controller manipulation of neither Senei nor Amigo is similar to physicians’ habits. In order to reach good operability, our team designed master-slave robotic catheter system [3][4][5][6] shown in Fig.1 and Fig.2 is motivated to imitate surgeons’ actions. In the catheter-based operation, two basic motions of catheter are insertion and rotation so on master side when physician drags the handle the step motor driven slide moves. Also, the handle is coupled with a motor by pulleys and a belt, which results in the handle rotating freely. In this way, the insertion and rotation motions of catheter are realized which is more suitable for physicians’ use. On the slave side, the catheter manipulator is capable of following motions on physician console because two encodes are used to detect translational distance and rotational angle on master side. The catheter manipulator design in Fig.2 is resemble to surgeon’s hand. Grasper 1 fixes catheter in cylinder like surgeon’s thumb and cylinder carries catheter to insert or rotate. When grasper 1 releases and grasper 2 fixes, the cylinder can go backward without any impact on catheter location. Besides, Yogesh et al.[7] proposed remote catheter navigation system which also consider the surgeons’ habit and allow them to manipulate real catheter. Fukuda et al.[8] designed linear step device which also simulates surgeon’s hand movement.

Fig.1. Master Side Physician Console [6]

Fig.2. Slave Side Catheter Manipulator [6]

For the surgery safety consideration, the endovascular surgery requires accurate position control. In order to improve the accuracy of catching catheter movement in physician’s console, a new laser mouse based master device is proposed in this paper for slave side control. The physician is able to manipulate the real catheter to move forward or backward. And meanwhile the catheter rotation can be realized. When the new device cooperates with slave side, catheter position change can be detected by laser mouse sensor and transmitted to slave side. The precise sample data ensures the synchronization between master device and catheter.
manipulator. Meanwhile, the new device is equipped with wireless laser mouse and it makes device more portable.

The paper is organized into the following sections. Section II will introduce the design of laser mouse based master device. How to use new device controlling the slave side catheter manipulator will be explained in section III. The experimental results are shown in section IV. Finally, the conclusion and future work are discussed in section V.

II. LASER MOUSE BASED MASTER DEVICE

In this section, we will first introduce the structure of laser mouse based master device. And then in order to accurately detect the catheter position changes, we will calibrate the catheter motion with mouse sensor sample data.

A. Structure of Master Device

In the endovascular surgery, typically the catheter will be inserted from patient’s femoral to target position. The catheter movements on master side decide how much it will travel in vessels. Thus, it’s a significant task to detect the catheter’s movements. In this paper, we use wireless laser mouse’s image sensor shown in Fig.3 to acquire catheter traveled distance.

![Image Sensor](image1.png)

Mouse used for distance measurement is introduced by our lab for providing force feedback to surgeon [9][10] or doing virtual-reality training system [11]. According to mouse working principle [12][13], the light source illuminates the surface and a lens is used to image the surface of the mouse pad onto sensor which located in the camera chip. The mouse works by comparing the image of surface that refreshed. Finally send the actual value of displacement to computer. On the contrary, when mouse is used for distance measurement, the mouse is static and catheter is analogy to surface which moves. Therefore, the image sensor is able to capture the catheter relative movement.

To assemble image sensor and catheter together, a 3D printed catheter fixer and image sensor holder are fabricated. As it is shown in Fig. 4, catheter is embedded into slim slot of fixer which confines its movements. But the slot space still allows catheter move forward/back and rotate freely. The image sensor holder is made in length 12 cm, width 8 cm and height 2cm. It is 165 gram and the holder combined with wireless mouse improves the portability of master side device.

![Catheter Fixer](image2.png)

B. Master Device Calibration

As the image sensor in mouse transform the irregularities of material texture into two dimension coordinate X and Y, it’s important to find the relation between the catheter really movement distance and coordinate change. Due to the fact that coordinates are pixel unite, we have to convert it into unite
millimeter. The translation action is conducted as shown in Fig. 8. In each insertion or extraction, the catheter is set to move 100mm with step 10mm and such processes have been down ten times. The acquired data are dealt with by linear function using Matlab. From Fig. 8, it is easy to see that linear relation is able to fit the experimental data. Such relationship is like expressed in equation 1

\[ \text{Disp} = 0.0195 \times P + 0.0135 \]  

(1)

where P and Disp are relative position change in pixel and catheter really translation displacement in millimeter.

\[ \text{Disp} = 0.0195 \times P + 0.0135 \]

After achieving the translation and rotation relationships, calibration can be conducted. In translation, the catheter inserts 100mm for five times and the measured data are transferred by Eq.1 into displacement showed like Fig. 9.

\[ \text{radian} = \frac{0.0195 \times P}{R} + 0.0135 \]  

(2)

Fig. 10 shows each measured distance. The results show that average value of measure distance is 100.34 mm and standard error is 3.26. Next we continued to do the rotation calibration and the catheter were required to rotate 1800 degree in counter-clock. The calibration is repeated five times and results are shown in Fig.11 and Fig.12. The average value of angle is 1818.4 and standard error is 182.89.

After the calibration work of laser mouse master device, the above derived results can be employed to control the slave side catheter manipulator.
III. MASTER-SLAVE COOPERATION SYSTEM

In this section, first we will introduce the laser-mouse based master and slave system. Then we will discuss how to use master device controlling the slave side device.

A. Overview of Laser Mouse based Master and Slave System

As shown in Fig. 13, the system consists two parts: laser-mouse based master side and slave side. In the master side, the image sensor can detect the catheter relative movements both in insertion and rotation. Such position changes are sent to master side PC and by above derived equation (1) and equation (2) convert to catheter’s real movements or rotation angle radian. Then catheter position data in master side are transmitted to slave side PC by Internet. In the slave sides, the catheter manipulator uses two step motor to realize the catheter insertion and rotation. The controller is DSP (TMS 320F28335) connected with slave side PC and it can produce pulses to control the two motors. The controller related circuit is shown in Fig. 14.

B. Control Strategy of System

To realize the catheter motion precisely following the master side catheter movement changes, in the slave side we adopt PID control strategy to control two step motors. Thus to complete the closed loop, two encoders are used to track the step motors. The whole control strategy is exhibited in Fig. 15, where $K_p, K_i, K_d$ are coefficients of proportional, integral and derivative control process respectively.

IV. EXPERIMENTAL RESULTS

In this section, we use above introduced laser mouse-based device as master side to manipulate the slave side catheter. To evaluate the control strategy performance, first we do catheter insertion and extraction repeatedly and then we roll it clockwise and count-clockwise several times.

The experimental results are displayed in Fig. 16 and Fig. 17. Figure 16 shows how will step motor response to catheter insertion work according to PID control. The blue line and red line represent catheter inserting displacements in master side and slave side respectively. The red line closely follows the blue line which means the slave side catheter moving according to master side laser sensor detected position.
changes. For the same experimental setup, we have done the catheter rotation action and the outcomes are shown in Fig. 17. On the one hand, such results prove that the laser mouse-based master device can precisely capture the operator’s action. On the other hand, the PID control method ensures the slave side catheter manipulator can closely follow the master side’s command no matter the translation or rotation.

![Fig. 16 The Catheter Insertion Response of PID Control](image1)

![Fig. 17 The Catheter Rotation Response of PID Control](image2)

**IV. CONCLUSION AND FUTURE WORK**

The robotic catheter operating system is a hot topic in endovascular surgery. Usually surgeons operate catheter carefully in order to avoid catheter piercing vascular wall. Therefore, in the master and slave system, the position control of catheter is a critical important task. The catheter movement in master side needs to be precisely detected and transmitted to slave side in order to realize master and slave side synchronization. For above considerations, our designed master side uses mouse sensor to accurately sample catheter position changes in pixel. And then such position changes are transformed into catheter real movement no matter in translation or rotation. According to calibration results, laser sensor based position measurement accuracy is pretty high. Additionally, slave side adopts PID strategy to control two step motors which are responsible for catheter insertion and rotation respectively. The experimental results demonstrate that the two motors in slave side follow the movements of catheter in master side well.

Possible future work can be done in following parts. First, the feedback force get from slave side is important for surgeon in master side. It’s urgent to realize the haptic force feedback for master side. Then, it would be better if the catheter movement in master side can be integrated with virtual-reality simulator. In this way, the visual feedback is helpful for surgeon’s operation.

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