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High Precise Haptic Device for the Robotic Catheter Navigation System

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***Abstract – A* study on haptic feedback of the master side for an interventional surgical robot system plays a critical important role in the master-slave vascular interventional surgery robot system with haptic feedback, and accuracy control of force feedback is an important means to improve accuracy of the vascular interventional surgery robot teleoperation. Focus on the problem of lacking haptic feedback and accurate control of force feedback in the master-slave interventional surgical robot system, we designed a novel operation control handle in the master, a more in line with the operation of human engineering during the operation process. It can not only get the haptic feedback information from the operation control handle effectively, but also realize the precise force feedback control of the master-slave vascular intervention surgical robot system. The theoretical analysis and the corresponding experimental verification clearly demonstrated that the doctors' operation on the master side is more real and more precise feeling the force feedback information, and effectively improves precision of the master-slave manipulation. The final results show that the accuracy control of force feedback was greatly enhanced in the aspect of reality and the operation efficiency during the doctor operation process.**

Index Terms: A master-slave robot, Haptic feedback of the master side, Kalman filtering, PID control

I. INTRODUCTION

Traditional minimally invasive vascular interventional operation refers to the doctor operates the catheter on-site and makes it into the blood vessels from the skin of the patients with incision, and the catheter is delivered to the lesion with the auxiliary medical image and makes the corresponding diagnosis and treatment [1]-[3]. In recent years, minimally invasive surgery with small trauma, less bleeding, fewer complications, safe, reliable and quick postoperative recovery has been widely used in clinic [4]-[6]. It is considered to be one of the most practical clinical medicine at present, but strong technical, complex operation, long operation time, X radiation injury and other defects, limiting the further development of vascular interventional operation [7]-[8]. But the organic combination of the robot technology and vascular interventional technology can effectively not only solve this problems, but also use the professional experience of doctors and robotics. The master-slave vascular interventional surgery robot is able to overcome the defects of traditional minimally invasive vascular interventional operation, leaving the surgeon away from the operating room and avoiding the harm radiation [9]-[11]. At present, the use of master-slave robot system operation has become a trend.

In traditional surgery, the surgeons operate surgical instruments directly, tactile information between instruments and human tissue can be directly felt by the doctors. During vascular interventional surgery, the surgeons are hard to get haptic information because of master-slave equipment operation. And for the doctors operation in the master, away from the patient operation on the slave side, and the mechanical device hold catheter and the doctor will lack a tactile guide, which not only affect the doctor hand-eye coordination operation, but restrict the operation experience of the surgeons [12]-[17]. It is also more likely to damage the patient's organs due to improper or excessive operation and increase the operation time and risk. Haptic feedback in many studies are involved, but the differences between the traditional force feedback mode and the force feedback through master-slave surgical instruments are very obvious. Study on haptic feedback of the master side of the surgical robot system and enhance the accuracy control of force feedback and allow the doctors to feel the real force accurately from the slave, which has become an important research direction in the aspect of improving the vascular interventional surgery robot force feedback control.

Now, many vascular intervention surgical robot systems have been used in clinical trials [18]-[24]. But in these systems, there are still many serious problems in the doctor operating process, especially the accuracy problems of force feedback. And all the commercial systems are open loop force feedback systems. At present, the United States Corindus company developed the robot assisted system CorPath 200 [25] for percutaneous coronary intervention (PCI). The propulsion device of the guide wire/catheter did not realize the force feedback function, but realize that promoting stress measurement from the proximal mechanism of guide catheter wire; Sensei Hansen, Canada Medical company, developed the vascular interventional robot systems [26] with powerful force feedback function, which measured it through the end of the guide wire/catheter, however, the doctors operation in the master is still not enough to feel the real force of the guide wire/catheter. That force feedback accuracy still exist some

problems. Currently being used in clinical surgery robot system all have problems of the lack of force feedback and force feedback accuracy. And precision of the force feedback mainly reflected on the doctors in the master where it can't accurately feel from the propulsion device to detect the guide wire /catheter force. Therefore, force feedback information from the end of the guide wire/catheter can't accurately back to the master. Meanwhile, this problem also directly restricts higher accuracy during the operation of master-slave vascular interventional surgery robot.

This paper designed a novel master operation control handle model which has improved from the previous one, and put forward the real-time force feedback closed-loop control strategy of the master-slave interventional surgery robot system. Based on the previous generation design of the operation control handle, this design has improved the master operation structure, letting the doctors clinical operation in the master more close to the traditional operation and the master handle more close to ergonomic operation; Then, during the operation, the surgeon will make it more real and more accurate feeling the force feedback information. And the new strategy not only can improve precision of the master-slave control, but also can enhance the operation efficiency and the sense of reality. In this paper, according to the following chapters introduction: the second part introduces the system structure of master-slave robot, especially introduces the master improved structure; the third part introduces the theoretical analysis and the master haptic feedback of the system and Kalman filtering; Fourth part shows the experimental scheme and the results of the analysis, the final conclusion will be given in the fifth part.

II. The Robotic System

A. System Description

Fig.1 shows the block diagram of the whole system structure, developed by Guolab [27]-[32]. The system consists of two main parts: one for manipulating the guidewire, also called the slave platform for the guide wire insertion; the other is a console for the physician, also called the master platform for the operation.

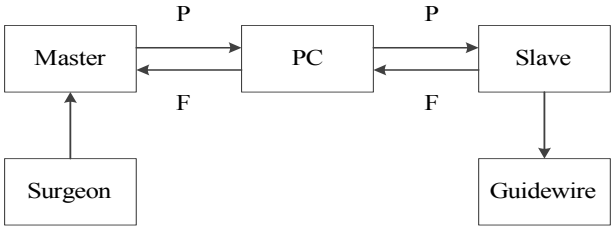

Fig.1. The block diagram of the whole system structure

Both parts are designed to mimic the experience a clinician would have during a hands-on operation. Surgeons tend to use their own skills when performing these types of operations, so the combination of a guidewire manipulator and a physician console represent a mode of operation familiar to clinicians. The master platform for the operation includes the Phantom, master control handle and image display. The slave platform for the guide wire insertion includes the guide wire/catheter delivery system.

The structure of the improved novel designed handle in the master showed in Fig.2. It is mainly consisted of a push sensor chosen to measure the force between the surgeon's hand and the handle, two cover pieces used to hold the phantom handle, and a long extra handle which designed to more accord with the surgeon's operation. The structure can accurately measure the feedback force of the Phantom when operating the guide wire. The two cover pieces is holding the Phantom's handle, when the surgeon hold the long extra handle remain stationary, the feedback force of the Phantom acted on the push sensor along the axis of the cover; when the surgeon hold the long extra handle push the handle forward, the compressional force is measured by the push senor, and the size of the measured force is the force acting on the surgeon's hand and the handle. From the novel handle, we can accurately measure the feedback force in the master.

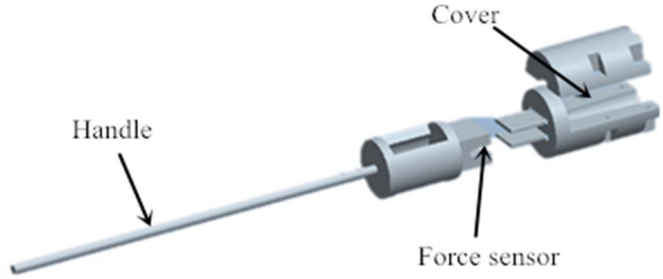

Fig.2. The structure of the master control handle

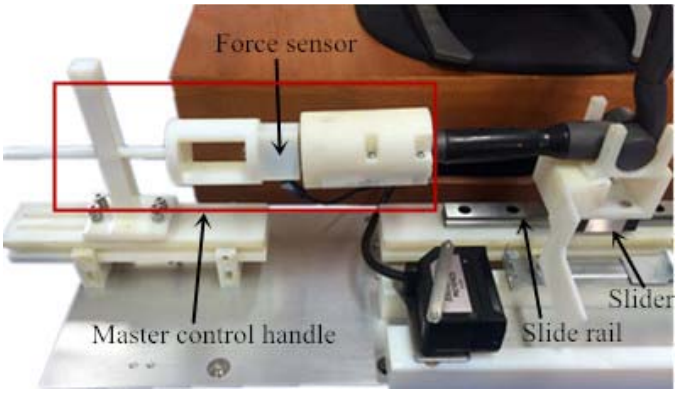

Fig.3. The master platform for the operation, and the red part is the real object

After adding the master control handle to the mater, the master platform for the operation shown in Fig.3. The master platform for the operation transfers the surgeon's hand movements to the guidewire and returns a measure of the resistance force on the guidewire. Surgeons hold the master control handle to input their commands; i.e. push, pull and rotate the handle. The cylinder of the guidewire manipulator will make the same movements with the master control handle. For the Phantom has 6 degrees of freedom and only two DOFs are needed when operating the guide-wire. We fixed the movement of the Phantom by program, and fixed the whole handle on the sliding block, while the sliding block is connected to the slide rail in case the unnecessary operation of surgeon's hand. As shown in the Fig.3, both the Y axis motion direction and along the Y axis rotation direction are chose as the two DOFs. The whole white parts connected with phantom's handle

are master control handle we designed. The novel design is more in line with the operation of human engineering during the operation process, and the design precision is much higher than the original design [33]. A force sensor embedded in the handle is much more accuracy than the previous one.

The slave platform for the guide wire insertion is mainly consisted of a guide wire clamping device and a linear motor with slide rail. Fig.4 shows the slave platform for the guide wire insertion. This paper focuses on the research of force feedback, and the following will mainly introduce the structure and principle of force measurement of the slave side. Seen From the Fig.4, the structure can not only push and rotate the guide wire well, but achieve detection of the force acted on the guide wire when operating the guide wire. A new mechanism for measuring the force acted on the guidewire has been developed. The whole load mechanism consists of force sensor, slider, slide rail, thrust bearing, linear bearing, ball spline pair, and guidewire gripper. The contact terminal of force sensor is connected with the force platform which is mounted on the sliding bearing. Slider and slide rail keep the axis direction with no static friction force. The linear bearing and the guidewire gripper keep the axis direction integrity. The ball spline pair can transmit the torque of electromagnetic brake without axial friction, so all the components connected with the guidewire can move in the axial direction freely. In view of this. When the guidewire is under stress, for the force sensor remain stationary and the other parts connected with the guidewire remain integrity, the thrust force of guidewire is measured accurately.

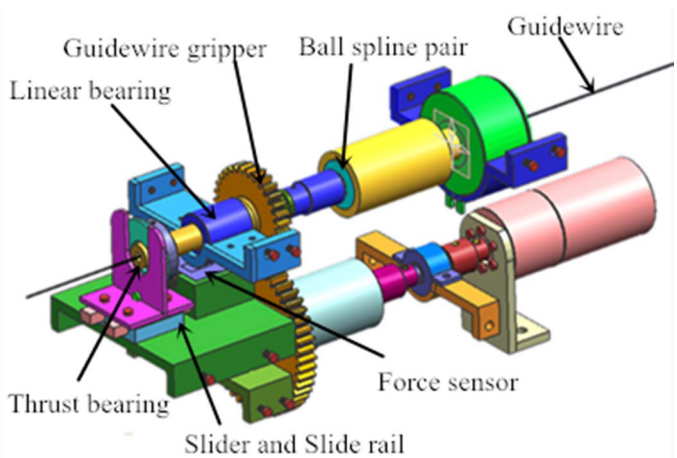

Fig.4. The slave platform for the guide wire insertion

B. Theoretical analysis and system control

The force feedback control of whole system shown in Fig.5. Though many master-slave robot systems have the force feedback, it is the open loop control and they all have a large error on the aspect. So we take the closed-loop control to improve the accuracy. In this paper, the research is focus on the haptic feedback of the master, the structure diagram of force detection shown in Fig.6, where f represents the force measured the proximal end of the guide wire/catheter and f' represents the resistance force measured by the phantom, the doctor push the control handle's force is F, the push sensor embedded in the master control handle detect the force f''. In time T_1:

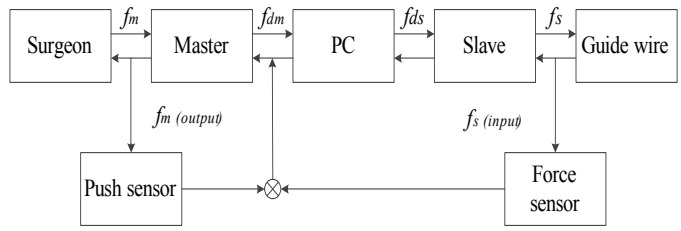

Fig.5. The closed-loop block diagram of the force feedback

When $F>f'$, the guide wire produce a speed in the blood vessels, the surgeon can obviously feel the existence of the feedback force during the operation, the push sensor is measured by the size of f';

When $F<f'$, the doctor can't push forward the control handle because of the guide wire resistance, at this time due to the control handle remains still, the push sensor embedded in the control handle measured the force value that refer to the size of the feedback force f', also the force value from the Phantom;

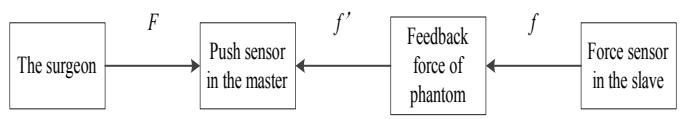

Fig.6. The block diagram of the detection force

In the next moment T_2, for the combined action of the surgeon's push force F and the resistance force of the guide wire at this time changed the force value of the slave side, go and return in following a circle. Therefore the push sensor embedded in the master handle measured f'' is the size of minimum (F, f'), which is also confirmed that the push sensor embedded in the master handle measured force is indeed the approximate value with the force value of the guide wire/catheter mechanism device. This design enhances the sense of reality that the surgeon felt during the operation.

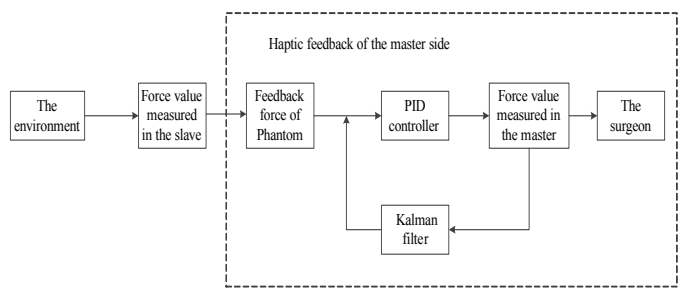

Fig.7. The haptic feedback of the master side

The haptic feedback control diagram of the master side shown in Fig.7. Output force on Phantom from the slave detection force as input, the push sensor in the master detects the force as output. In order to avoid the surgeon have the hand shaking and the possible structure of friction. In this paper, firstly, the Kalman filter is adopted to control the sensor measurement values in the master operating structure, then the simple closed loop PID control is used to realize the precision control of feedback force, and ultimately the surgeon will feel the accurate force feedback in the master.

III. Experiments and Results Analysis

In order to prove the superiority of the new handle structure and the algorithm, we make some experiments.

First of all, we verify that the size of the force measured by the push sensor embedded in the master control handle is the value f' of the feedback force returned on Phantom. Due to the research focus of this paper is on the study of haptic feedback in the master, in this paper, we presumed that the force of the slave were recorded accurately by the Phantom. And we set that the input value of the feedback force of constant Phantom is 0.5N.Through the experimental personnel move the master handle to forward and backward, the numerical value of the push sensor embedded in the master handle is recorded. In order to avoid accidental experiment, the experimental process records the data of 6 operation of the experimental personnel. According to the theoretical analysis above, this paper makes a reasonable prediction that when the master control handle is pushed forward by the experimental personnel, the recording value of the push sensor embedded in the master control handle should be similar to the 0.5N, and when the master control lever is backward, the recording value of the push sensor should be similar to the 0N.

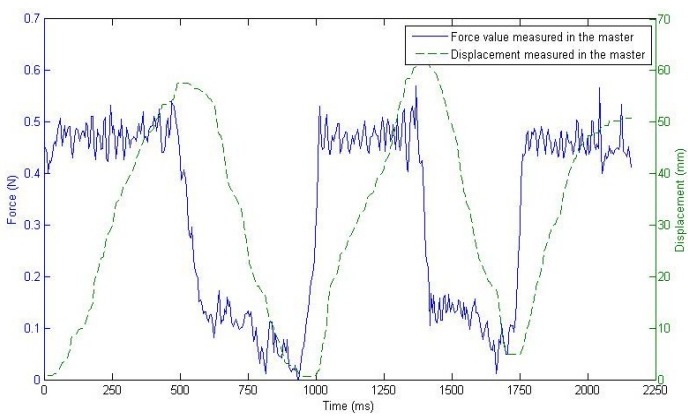

Fig.8. The surgeon's haptic feedback and displacement information of the master side

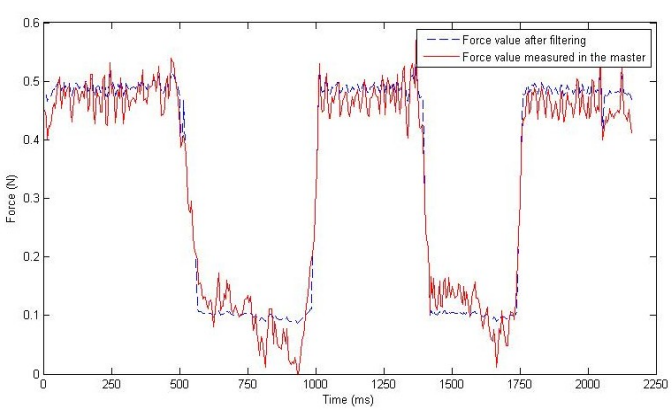

Fig.9. The actual force value after adding the Kalman filtering

The surgeon's haptic feedback information of the master side during the operation is shown in the Fig.8, 9. The blue curve is shown in Fig.8 (the feedback force of the master side) basically meet the expected theoretical analysis. However, due to the presence of the hand shake of experimental personnel in the operation and backward operation may exist impulse interference, the result still has a partial fluctuation. The actual force value after adding the Kalman filtering is shown in Fig.9, which makes the results more consistent with the input force values. But obviously when the backward operation, there are still about 0.1N error, and there is still a 0.1N error in this part experiment. In order to improve the error, PID control is also required to make it closer to the input. Anyway, the first experiment verifies that the magnitude of the force measured by the push sensor embedded in the master control handle is indeed the feedback force value f on the Phantom.

Then, according to the control block diagram of the haptic feedback system, the measured value after the filtering and the value of phantom are given as the output and input to carry out the force feedback PID closed loop control algorithm, verifying the actual feedback force of the experimental personnel in the process of the master operation and record the error value of the feedback force. Similarly, in order to avoid the chance of experiment, the experimental process records the data of the 6 operation of the experimental personnel.

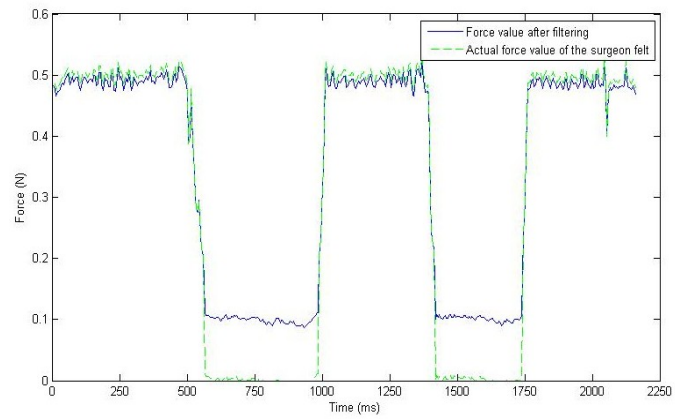

Fig.10. The actual force value with/without adding force feedback PID closed-loop algorithm

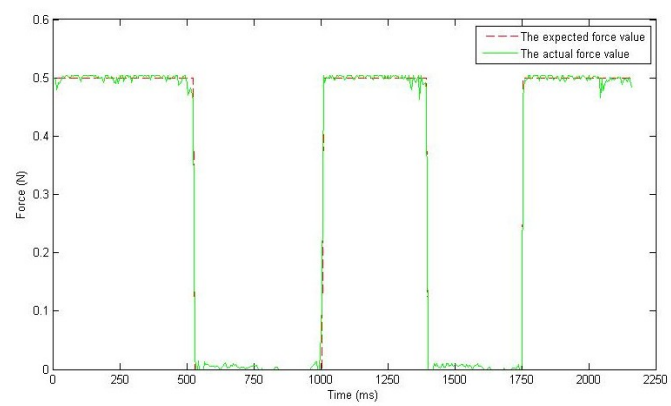

Fig.11. The comparison between the expected values and the actual values of the push sensors.

The actual force value of the output curve (green curve) after adding force feedback PID closed-loop algorithm is shown in Fig.10. As seen from the Fig.10, when the experimental personnel operating backward, PID closed-loop control

algorithm effectively carry out the compensation of the force, making the actual force measuring the force value much closer to zero. The comparison between the expected values and the actual values of the push sensor is shown in Fig.11. The red curve is the expected value, also the feedback force value of phantom in the ideal state. It can be seen from the graph that after adding the master structure of the novel operation design and filtering algorithm, the maximum error of the feedback force value will lower to 0.02N. Compared with the previous designed structure, the novel controller greatly improved precision of the master-slave manipulation and made the master operation of surgeon more real and more accurately feel the force feedback information.

IV. CONCLUSION

A novel type of master control handle is designed in this paper. It not only can effectively obtain the haptic feedback information of the surgeon on the master side during the operation process, but also realize the precision force feedback control of master-slave interventional surgery robot system. Based on the previous generation design of the operation control handle, this design has improved the master operation structure, letting the doctors' clinical operation in the master more close to the traditional operation and the master control handle more close to ergonomic operation. Through the experimental verification analysis, not only the magnitude of the force measured by the push sensor embedded in the master control handle is indeed the feedback force value f on the Phantom, and after adding the master structure of the novel operation design and filtering algorithm, the maximum error of the feedback force value will lower to 0.02N, but also the doctors' operation on the master side is more real and more precise feeling the force feedback information, and effectively improves the precision of the master-slave manipulation. The research of haptic feedback of the master side for an interventional robot system has improved the force feedback closed-loop control structure of the whole system.

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