Proceedings of the 2015
IEEE Conference on Robotics and Biomimetics
Zhuhai, China, December 6-9, 2015

An Interventional Surgical Robot System with Force Feedback

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***Abstract* - The interventional surgery is a kind of minimally invasive treatment. To achieve the real-time diagnosis and strengthen the doctor operation sense of reality and the operation efficiency, the accurate control of force feedback plays an important role. Based this, we utilize the Phantom Omni as the master manipulator and construct the master-slave robot system with the force feedback closed-loop control. We put forward tracking control strategy and real-time force feedback control strategy. By measuring the proximal guide wire force and the force between the surgeon's hand and the handle used on the Phantom, the force feedback closed-loop control can effectively eliminate the loss of mechanical impedance of force feedback information. And the novel interventional surgical robot system will simulate the procedure of the doctor's hand to operate the guide wire, and providing haptic feedback to the doctor. In this paper, the experimental results show that the accuracy control of force feedback is greatly enhanced in the aspect of security and the operation efficiency.**

***Index Terms* - Interventional surgical robot system, Force feedback, Remote control, Fuzzy PID**

I. INTRODUCTION

In recent years, minimally invasive interventional surgery with the advantages of low risk, fewer complication and quick recovery has become more and more popular in clinic treatment. However, there are also some deficiencies in the area of interventional surgery: 1) Doctors need long-term working under X-ray, which would cause great damage to the doctor's body, especially the spine. 2) The doctors must have rich knowledge about anatomy and a lot of operating experience. 3) Heart and head blood vessel are very fragile and narrow. 4) Contact force between the vessels and catheter cannot be detected or directly shown to the doctors for warning. So any wrong operation could easily lead to the failure. Recently, we can address these problems by combining robot technology and the vascular interventional technique [1]. Then, the interventional surgical robot system appears as the development of the robot technology.

In the past years, some great products have been designed. One of the most popular products is Sensei Robotic Catheter System manufactured by Hansen Medical [2]. This System provides more stability for surgeons in catheter placement compared to manual techniques, so it can allow for more precise manipulation and less radiation exposure to the doctor. Catheter Robotic Inc. produced a remote catheter system called Amigo [3]. This system has a robotic sheath to steer catheter at a nearby workstation, and it is similar to Sensei system in manner. Magnatecs Inc. produced the 'Catheter Guidance Control and Imaging' (CGCI) system [4]. This system has 4 large magnets placed around the table, with customised catheters containing magnets in the tip. The catheter is moved by the magnetic fields and controlled at a nearby workstation. The Stereotaxis Inc. developed a magnetic navigation system called the Stereotaxis Niobe [5]. Yogesh Thakur et al. developed a kind of remote catheter navigation system [6]. This system allowed the user to operate a catheter manipulator just like operating a real catheter. So surgeon's operative skill is able to be applied in this system

However, there are also some disadvantages about these products. Most of them aren't in conformity with the surgeons' custom and they also require extensive training to ensure accurately performing the interventions. And the diameter of the catheter will limit the products in some difficult operations. Moreover, to measure the contact force between the vessel and the catheter is very hard. Lastly, they can only measure their force feedback through the catheter, and a potential problem of a remote catheter control system is the lack of mechanical feedback, which means that the current system wouldn't receive any force feedback from the slave system when controlling a catheter.

In the previous research, there are many achievements around the world. Shuxiang Guo put forward a new kind of pipe robot control system, the system uses a master-slave control mode and it achieves the remote operation [7]. Ganji set the heart radiofrequency ablation catheter navigation platform [8], and did the corresponding catheter experiment. RS Penning, D Glozman and RS Penning did some algorithms research in pipe robot system closed-loop control, those researches expect control catheter to the specified location [9-11].

However, existing studies have not really realized the function of force feedback, which leads to the lack of important guidance information during the operation. It seriously impacts on the efficiency and safety of operation. Force feedback implementation consists of two key technologies: force measurement and providing feedback force [12-14]. In order to solve these problems, this paper proposes a new interventional surgical robot system.

Position tracking errors between the master and slave platform will be minimized and the slave side of the system will simulate the doctor's hand movements for the operation catheter or guide wire [15]. And the use of mechanical sensor integrated in the catheter manipulator complete testing of resistance at catheter. A new doctor’s console is designed. It can detect accurate operation commands of doctors and provide force feedback for the surgery [16-18].

This paper described the complete system and put forward the Fuzzy PID control to decrease the tracking error. Also, this paper discussed the performances of the force feedback control. The paper will be introduced as follows: The second part introduces the interventional surgical robot system; the third part shows the controlling methods and the experiments. And the final part is the results and conclusions.

II. The Robotic System

The system consists of two parts: the master platform for the operation and the slave platform for the guide wire insertion [19-23], as Fig 1. The master side is surgeon’s console, mainly providing a simulation operation and force feedback for the doctor, and collecting control commands of the doctor from the guide wire in the operation. The slave side, catheter manipulator, will be responsible for the control of guide wire in the patient’s intravascular.

Fig.1 Robot System

A. The Slave Platform

The slave platform, as shown in the Fig 2, will imitate movements of physician's hand to operate the guide wire. The slave system is a three-axis linkage mechanical structure. Two of the motors are motion axis, one of the motor controls the linear motion and another controls the rotation motion. The other motor is responsible for the control motion. It is responsible for controlling the guide wire if it is clamped or relaxed [24].

In the Fig.2, part A consists of a servomotor and a linear slide. This part of the linear motion is controlled by SMC motion control card, and obtains the precise position feedback data.

The inner of the B structure is a rotating parts and control part, and the control part made the guide wire to be clamped or relaxed. The section of slave motion structure composed of those two motors can ensure that the whole process of intervention operation don't need a doctor in the operating room for other manipulation, and it ensure the doctors can finish the whole operation process by remote control with using Phantom Omni. At the same time the part B is within a FUTEK mechanical sensor, through the sensor can accurately measure the force feedback of the slave system transferred from the guide wire, and it will transfer the feedback to the master side. The part B is the core of the guide-wire manipulator [25-27]. And the structure of inside is shown Fig 3.

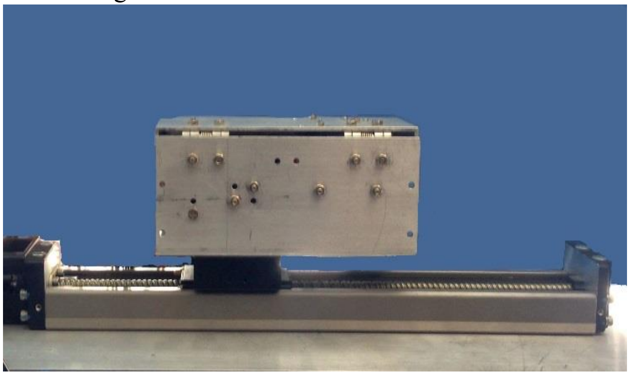

Fig.2 the Slave Platform

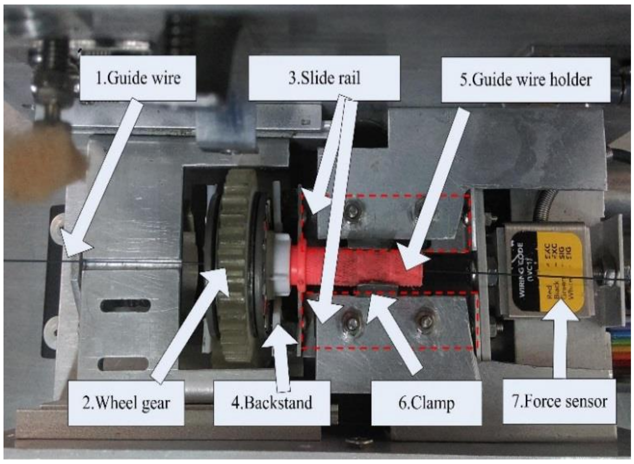

Fig.3 the Guide Wire Manipulator

The process of guide wire movement is show in the Fig.4. The red arrow marks the position and direction of the guide wire. In the step 1, the clamp is loose and manipulator go forward, the guide wire will go forward. During movement, resistance of guide wire will be passed on to the guide wire holder. Through the back-stand fixed on the guide wire holder, the resistance will passed to the force sensor. Because the back-stand on the slide rail, the frictional force is extremely small. This mechanism can guarantee the measuring accuracy. In the step 2, the clamp is loose and wheel gear rotates, the guide wire will rotate. In the step 3, the clamp is gripping, wheel gear rotates and manipulator falls back, the guide wire holder will be loose and guide wire keeps still. In the step 4, wheel gear rotates and the clamp is loose, the guide wire holder will be gripping and guide wire keeps still. After completing procedures, manipulator returns the initial state and guide wire forward 50mm and rotate 90 degrees [28].

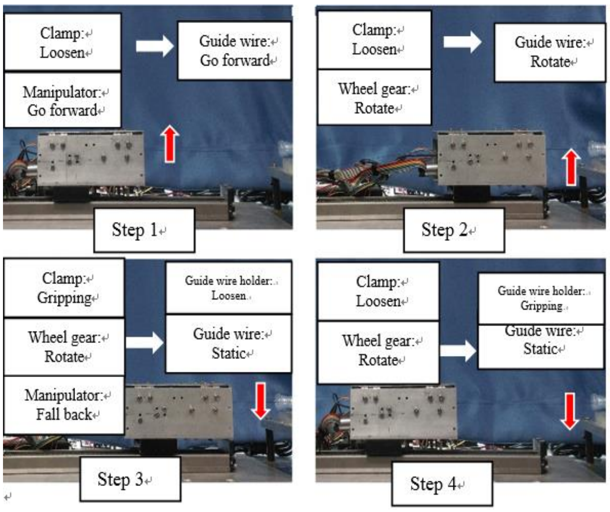

Fig.4 the process of guide wire movement

B. The Master Platform

A Phantom Omni is employed as the master manipulator. Because 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. As shown in the Fig.5, the Y-axis motion direction and the Y-axis rotation direction are chosen as the two DOFs. When the surgeon pushed the handle along the Y-axis, then the slave completed the push for the guide wire. When the surgeon rotated the handle along the Y-axis rotation direction, then the slave completed the rotation for the guide wire.

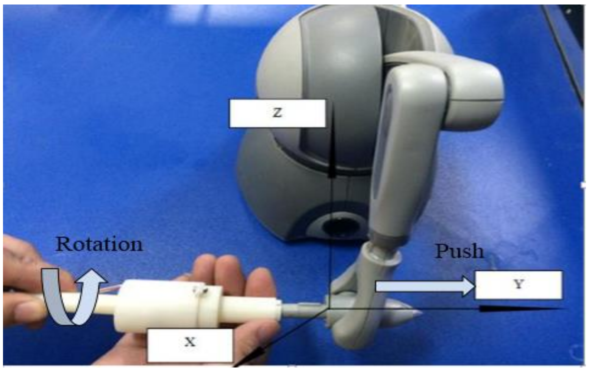

Fig.5 the Phantom Omni

The Phantom's instructions show that its feedback force precision of output is very high, and the feedback force acted on the direction of the Y-axis. In order to measure the force between the surgeon's hand and the handle when operating the guide wire, we designed a new handle, and there is a force sensor embedded in the handle. The force sensor has a high sensitivity. The force can be measured by the force-sensor when the Phantom is working. By using the novel handle, the feedback force in the Y-axis can be measured accurately. The Fig.6 shows the structure of handle used on the Phantom. It is mainly consisted of a force sensor, an interconnecting piece, two splints and a cover. The structure can accurately measure the feedback force of the Phantom when operating the guide wire. The interconnecting piece is connected with the Phantom, when the surgeon hold the handle remain stationary, the feedback force of the Phantom acted on interconnecting piece reach the Splint 2 through Part 2. Because the Splint 1 and Part1 are connected with the Handle, the corresponding force is measured 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.

C. The Vessel Model

In this paper, we do the experiments with the vessel model, as shown in Fig.6. Firstly, we transport the catheter to the certain place we want. Then through our system, we can transport the guide wire to the place for PTRA (percutaneous transluminal renal angioplasty) or to the place with CTO (Chronic total occlusion).

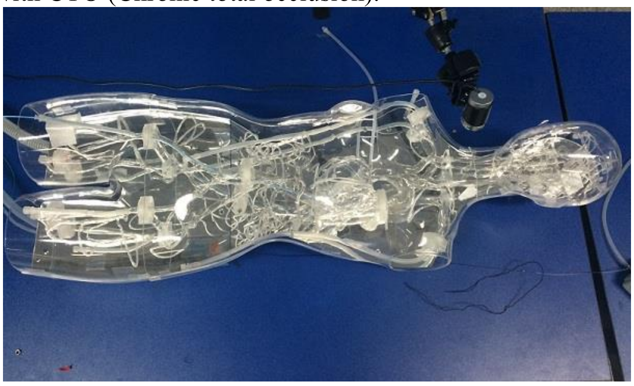

Fig.6 the Vessel Model

III. The Controlling Method Of The System

A. The Master-Slave Tracking Control

The whole system control of the robot includes the master-slave tracking control and force feedback control. According to the characteristics of this system we use the Fuzzy PID closed-loop control to achieve tracking control. The controller block diagram is shown in the Fig.7.

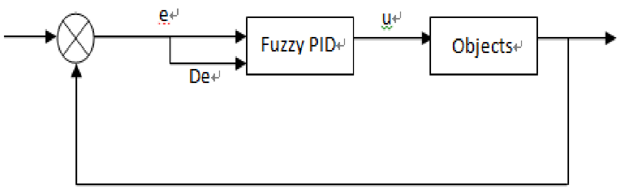

Fig.7 the Fuzzy PID controller

According to input of the error and error change rate of the controller, it will input to the fuzzy PID controller to choose the strategy, and the output value of PID controller will adjust the parameters of the PID controller according to the strategy that chosen by the e and De. In this system, we build a model that the motion results of the master part is the input at the same time the results of the slave part is the output. The Equation (1) is shown as below:

$$y[i] = x[i] + e[i] + De[i] \quad (1)$$

In this system, the motion of this system is able to estimate. So we choose the motion parameters, which happened before to correct the current motion. In order to avoid the over correction and to keep the error small enough, we made a table to choose the appropriate method, and then we chose the appropriate parameter from the table.

B. The Force Feedback Control

Many master-slave robot systems use the open loop control to achieve force feedback and have a large error. So we utilize the closed-loop control to improve the accuracy. Fig.8 shows the controller of the force feedback. Specific methods are as follows: the real-time force feedback signal from the slave will be collected as input, the actual force feedback signal from the master will be collected as the output. Through signal processing and PID control, both of two signals reach the same accuracy.

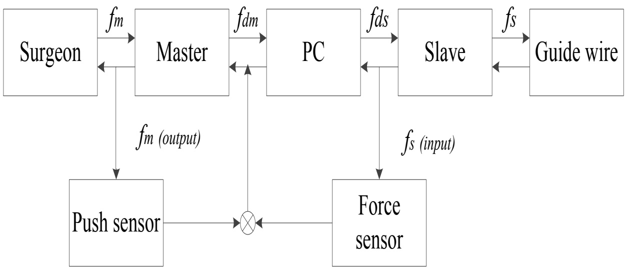

Fig.8 The force feedback control

In the diagram, fm represents the force between the Phantom and the surgeon. fs represents the force between the slave and the guide wire. fdm represents the force between the master and the torque. fds represents the force between the slave and the torque.

In order to improve the accuracy of the force feedback, a PID controller is adapted to achieve the closed-loop force feedback control. So we can effectively achieve the error elimination of the force feedback. In order to decrease the error as soon as possible, the system choose the proper PID parameters to get the optimal control.

IV. Experiments And Results

A. The Performance of Position Tracking Control

We do the experiments to verify if the controlling method is suitable for this system. We use the phantom Omni to do the straight linear motion and the motion results will show on the computer timely. The motion results of the slave system getting by the encoder will be sent to the computer timely.

Fig.9 and Fig.10 show the position tracking experimental results. According to these results it can be found that the dynamic tracking performance of the system is stable. The error is between -1 mm to 1 mm and the speed of motion is suitable in the MIS.

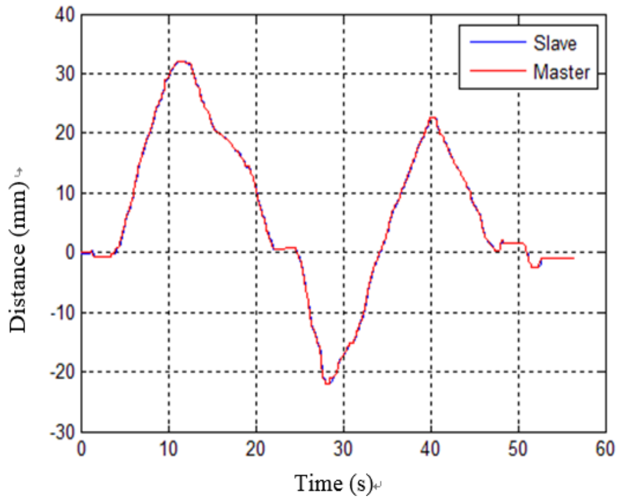

Fig.9 Position Tracking of the master-slave system

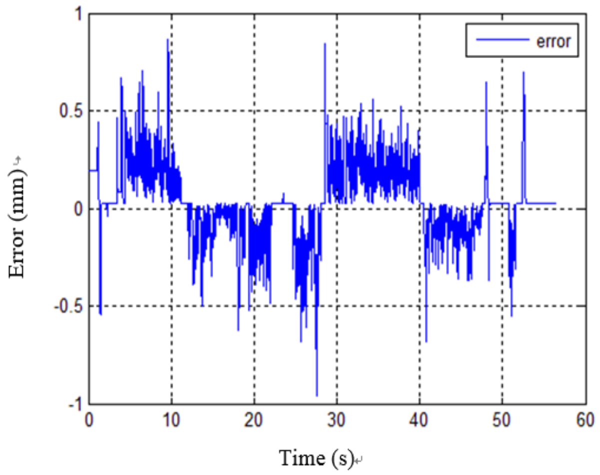

Fig.10 the Tracking Errors

B. The Performance of the Force Feedback Control

In order to evaluate the effects of the force feedback strategy, we take the comparative method to complete the two group experiments. In each group, we invited 10 volunteers to carry out the experiments and calculated the average value.

In the first group experiments, when operating the guide wire, we use the specific signal to simulate the real force feedback signal resembling to the force acted on the guide wire. A previous program generates the special signal. The force sensor loaded in the clamping device can measure the force, and the PC can get the real value on the screen. The value acted as the real input value of the force feedback signal. At the same time, the Phantom keep fixed position in the master, through the embedded force sensor to detect the force between the surgeon’s hand and the handle used on the Phantom. The value displayed on the screen acted as the actual output value of the force feedback signal. The blue curve in Fig.11 represents the true value of the force feedback signal from the slave as the input, and the black curve represents the actual value of the force feedback signal detected by the pressure force sensor in the master.

The X-axis represents the time, and the Y-axis represents the force.

In the second group experiments, we join the closed-loop force feedback algorithm in the system. Firstly, we get the curve fitting for the two signal data, the real force feedback signal from the slave as the input value, the detected force feedback signal in the master as the output value, obtaining the fitting function. Then the system are controlled by the PID algorithm, reaching the force feedback precisely control. The red curve in Fig.12 represents the improved force feedback signal detected by the force sensor after adding the PID algorithm. From the two pictures, the error values between the real force feedback signal and the improved force sensor signal can be compared obviously.

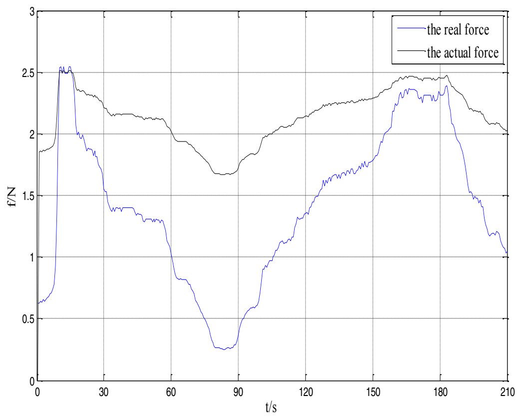

Fig.11 The Results of the first group experiments

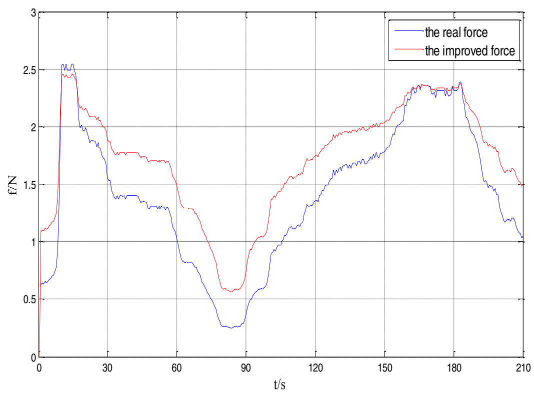

Fig.12 The Results of the second group experiments

From the figure, we can find that many force feedback systems can't guarantee that the feedback force acted on the surgeon's hand is the same as the current stress on the guide-wire. In fact, there is a large accuracy problem for general force feedback systems. And the Fig.12 shows that the closed-loop control of the force feedback improves the accuracy of the actual value of the force feedback in the master. According to the Fig.11, the maximum error can be reached 1.42N. After joining the closed-loop force feedback algorithm, the maximum error between the improved actual value of the force feedback and the real value of the force feedback decrease to 0.48N. Thus the actual value of the force feedback in the master is much closer to the real value after adding the force feedback algorithm. In other words, the surgeon can feel more real and more precise force feedback information during the operation process. This result also reflects that the force feedback algorithm can greatly improve the efficiency and high accuracy.

V. CONCLUSIONS

This paper designed a novel interventional surgical robot system with force feedback. The slave system adopts the Fuzzy PID controller and it has good real-time performance and accuracy. The results of motion are suitable for the minimally invasive interventional surgery. And the master system adopts a closed-loop force feedback algorithm to achieve force feedback. By simulating the insertion of the guide wire, the real values of the force feedback from the slave and the actual values of the force feedback in the master are compared, the results indicate that the closed-loop control can reduce the error values between the real force feedback value and the actual force feedback, and the surgeon can feel more real and more accurate force feedback information. It also improved the security and precision of the master-slave manipulation, so as to strengthen the sense of reality and the operation efficiency during the operation process. Though there are some shortcomings of this system, like ignoring the friction in the structure, it also has great and profound meaning of training.

ACKNOWLEDGMENT

This research is partly supported by the National Natural Science Foundation of China (61375094), National High Tech. Research and Development Program of China (No.2015AA043202).

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