A Novel Force Feedback Interventional Surgery Robotic System

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Abstract - The interventional therapy combining with modern high technologies, is a kind of minimally invasive treatment. In order to achieve pathological diagnosis and local treatment, catheter and guide wire are delivered to patients’ lesions through their blood vessel with the guidance of DSA image. Interventional therapy has advantages of small trauma, rapid recovery. And it has become the developing trend of the future medicine. Presently, the interventional treatment has some shortages. For instance, the patients could not be separated from the surgeons. Also, it is difficult to measure the front collision force of the guide wire. To solve this problem mentioned above, the phantom omni was used as the master controller, and a new novel of interventional operation slave system equipped with force feedback structures was designed. Fuzzy PID looped control was adopted in this system, and the dynamic performance of the surgery robotic system was analysed in this paper.

Index Terms - Minimally invasive interventional surgery, Master-slave system, Force feedback, Fuzzy PID

I. INTRODUCTION

Minimally invasive interventional surgery has a lot of advantages such as no operation, less bleeding, fewer complications, small trauma, quick recovery, etc. Therefore, it becomes more and more popular in the treatment of cerebrovascular diseases [1]. However, currently human intervention operations have some deficiencies: 1) Doctors need to work long hours under X-ray, and so the doctor is under the radiation, which will endanger their health. 2) The doctor must have rich knowledge and many years of operating experience of heart and head blood-vessel to avoid making the mistakes during the surgeries. 3) The doctor's wrong operation easily leads to a perforation, and it will cause the failure of surgery, which will endanger patient health. Recently, with the development of robot technology, it can be very effective to solve this problem by combining robot technology and the vascular interventional technique [2].

In the past few years, some products have been developed. One of the most popular products is a robotic catheter placement system which is called Sensei Robotic Catheter System supplied by Hansen Medical [3]. This System provides the surgeons with more stability in catheter placement with the Artisan sheath compared to manual techniques, so it can allows for more precise manipulation with less radiation exposure to the doctor. Catheter Robotic Inc. produced a remote catheter system called Amigo [4]. This system has a robotic sheath to steer catheter controlled at a nearby work station, and it is similar to Sensei system in manner. Magnatecs Inc. produced their ‘Catheter Guidance Control and Imaging’ (CGCI) system [5]. 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 is controlled at a nearby work station. The Stereotaxis Inc. developed a magnetic navigation system called the Stereotaxis Niobe [6]. Yogesh Thakur et al. developed a kind of remote catheter navigation system [7]. 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 custom of surgeons’ operations and they require extensive training to obtain the expertise to ensure correctly performing the interventions. The diameter of the catheter is also a problem which limits the products in some difficult operations. Moreover, to measure the tip force by the system is very hard because of their structures. Lastly, they can only measure their force feedback by 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. Shu-xiang 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 [8]. Ganji set the heart radiofrequency ablation catheter navigation platform [9], 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 [10-12]. At the same time, many research institutes did some jobs in catheter and guide wire research. Due to the stringent requirements for the safety of interventional surgery, position tracking error between master and slave must be minimized during the operation. Therefore, aiming at this problem caused in master-slave control system, this paper provided a system with Fuzzy PID control to decrease the tracking error. This paper also discussed the dynamic performance analysis of the slow motion and the fast motion to verify that the system can be used in the current operation environment.
II. INTERVENTIONAL SURGERY ROBOT SYSTEM

Interventional surgery robot system structure consists of two parts, master side and slave side. The master side is the control part of the robot system for operation, and the slave system is the control part of the guide wire. In this intervention operation system, the physicians do the surgery from the master side by using a phantom omni, and the slave system is a self-designed multi-axis linkage structure, which is controlled by SMC motion control card and PMAC motion control card. The movement process of slave part is similar to the manipulation that doctors use the guide wire to do the interventional surgery. So it ensures the consistency of the master-slave system movement. The master part Phantom omni communicates with the computer by IEEE 1394 protocol, and the slave system communicates with the computer through PCI bus protocol. This robot system is for the experimental stage, so at present it is not with the network communication part. The overall system diagram is as shown in the Fig.1.

In the master-slave system, both the linear sliding table servo motor and two EC brushless dc motors of the slave system have their own encoder. Therefore, both the distance of the linear motion and rotation angle can be calculated accurately through the encoder in order to achieve the desired control results. In the master side, the phantom omni operation lever type design can ensure the master side manipulated by the surgeons going forward and doing rotation maintaining a high level of consistency. On the choice of controller, because of the complexity of the master-slave system and the uncertainty of operating factors, the system adopts the way of fuzzy PID control. This control mode guarantees the accuracy of the slow motion and fast motion at the same time.

A. The slave system

The slave system is shown in Fig.2, this part is placed in the operating room, and surgeons manipulate the master side remotely. 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 the other controls the rotation motion. Another motor is responsible for the control motion. It is responsible for controlling the guide wire if it is clamped or relaxed. In this paper, we use a vessel model to replace the real environment. The vessel model is shown in Fig.3.

As it shown in the Fig.2 (a), the A part is for linear motion, it consists of a servo motor 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 B 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 part which transferred from the guide wire, and it will transfer the feedback to the master side.

The whole process of the movement is introduced as below. Structure B fixed in the part A straight line slide table. When need the guide wire do the linear motion, the control part of B structure clamp the guide wire and the part A will take the part B to go forward. When need the guide wire do rotation motion, the control shaft of the part B makes the guide wire clamped (clamped by the guide wire reversing device shown in Fig.4) and did the same rotation motion as master side. When structure B go forward to the limit position, the surgeons need to go back in order to complete the surgery, and the control motor will relax the guide wire with the motion of the rotation axis motor. In order to complete this work, both of those two motor will do a multi-axis linkage movement. After doing this work, due to the overall
mechanical structure of part B is apart from the guide wire, it can do the go-back motion. At the same time to prevent guide wire sliding, a device out of the part B will clamp it at this time. When part B returns to the appropriate location, it can continue to do forward motion. Before it does the forward motion, the guide wire should be clamped for sure. It should be pointed out that due to the force measurement in the part B, so it needs to do zero mechanical measurement every time after the process of relaxing and clamping, otherwise it will produce great error of force measurement.

In this paper, we do the experiments with using the vessel model. It is the model of cardiovascular. Firstly, we transport the catheter to the 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). The vessel model is shown in Fig.3.

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**B. The master system**

The master part is a phantom omni (shown in Fig.4). We employ the phantom omni as the master part of the robot system. The phantom omni has 6 Dofs, but only 2 Dofs are enough for guide wire operation, so we choose the X axis as the linear motion axis and the Y axis as the rotation motion axis. Firstly, its displacement resolution can reach about 0.055 mm. In the process of experiment the surgeons manipulates
we made a table to choose the appropriate method. Then we chose the appropriate parameter from the table.

IV. THE RESULTS OF DYNAMIC PERFORMANCE

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. At the same time, when we control the phantom omni to do the straight linear motion, part B as shown in Fig.2 (a) will do the same motion. This motion is controlled by a SMC motion control card which is connected to the computer by PCI. The motion results of the slave system getting by the encoder will be sent to the computer timely. And we use these two data to analyze the result of slow motion and the fast motion. The sketch map of the experiment is shown in Fig.7.

Fig.7 The sketch map of the Master-Slave System experiment

Fig.8 and Fig.9 show the position tracking experimental results. According to these results it can be found that the dynamic performance of the system in a catheter is stable under the slow motion. Dynamic tracking performance of the system error is between -1 mm to 1 mm, and the speed of motion is suitable in the MIS. The slave system is a PID control system with appropriate parameters. And when we control the slave system apart from the master part, the linear movement precision of the slave system is about 1 micron.

Fig.8 Position tracking of the master-slave system
Fig.8 and Fig.9 show the performance of the system in low speed. The results show that the system is relatively stable when doing this motion. Fig.10 and Fig.11 show the performance of fast motion. For the forward motion is the same as the back motion, we just choose the result of forward motion. From this we can find this system is easily influenced by the operator, however our Fuzzy controller solved this problem efficiently. When there is a fast movement, the controller will choose the appropriate strategy and decrease the error appropriately. And this system will have little cumulative error.

V. CONCLUSIONS

This paper designed a complete device of master-slave control of catheter interventional operation system with force feedback. The master side takes the use of the Phantom omni instead, and we design a new type of mechanical structure as the slave system. The control system adopts the Fuzzy PID controller and it has good real-time performance and accuracy. The results of quick motion and slow motion are both suitable for the minimally invasive interventional surgery. However there are some shortcomings of this study: not to design a more suitable master side structure for the interventional surgery but to take the phantom omni instead; The data collection of the force feedback from slave system is easily to be affected by the friction in the structure, and it will take some difficulty to do the data collection. So it has to be said that the structure still need some development. However, this master-slave system is still a good experimental operating device for the current remote catheter interventional surgery doctor, which has great value of training.

ACKNOWLEDGEMENTS

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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