

An Improved Master-Slave Interventional Surgery Robotic System with Force Feedback

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Abstract - The interventional surgery is a minimally invasive treatment, which uses the modern high technology. It takes the special catheter, guide wire and other precision instruments to import in the body to do the pathological diagnosis and local treatment under guide of medical imaging equipment. Interventional surgery has excellent characteristics like no operation, small trauma, rapid recovery, etc. It is one of the developing trend of the future medicine. Now, the interventional treatment has some shortage such as the radiation exposure on surgeons, and it is difficult to measure the front collision force on the guide wire. In this paper, we did some improvements on the master controller on the basis of Phantom, and analyzed the dynamic performance from the surgery robot system.

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

I. INTRODUCTION

Compared with normal surgeries, minimally invasive interventional surgery has many advantages, such as less bleeding, fewer complications, small trauma, quick recovery, etc. It is getting more and more popular in the treating of vascular disease now [1].

This surgery is not friendly to doctors because of the radiation in the operation room. The health condition of doctors is terrible. Because they have to be exposed in the radiation environment. The surgery depends on doctors' experience too much. People have found a way to solve these problems. Combine robot technology with vascular interventional technique. [2].

In recent years, several kinds of interventional surgical robot systems were developed. Sensei Robotic Catheter System, which is developed by Hansen Medical is one of these products [3]. This system reduced the exposure to doctors by providing surgeons more stability in catheter placement with the Artisan sheath compared to manual techniques. Catheter Robotic Inc. produced a remote catheter system called Amigo [4]. This system has a robotic sheath to steer catheters controlled at a nearby work station, and it is similar to Sensei system in manner. Magnatecs Inc. produced '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 operated by the magnetic fields and is controlled at

a nearby workstation. 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 users to operate a catheter manipulator just like operating a real catheter. So surgeons' operative skill is able to be applied to 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 to ensure the correctly performing of the interventions, extensive training is required. The diameter of the catheter is also a problem which limits the products in some difficult operations. Moreover, the tip force of the system is very hard to be measured because of their structures. And a potential problem of a remote catheter control system is the lack of mechanical feedback. It means that the current system wouldn't receive any force feedback from the slave system when controlling a catheter.

In the previous researches, there have been several achievements around the world. Shuxiang Guo designed a novel robot control system with master-slave control mode [8]. Ganji set the heart radiofrequency ablation catheter navigation platform and similar catheter experiments [9]. RS Penning and D Glozman researched how to operate catheters to move to the target [10]-[12]. At the same time, many research groups did some jobs in the catheter and guide wire research. Shuxiang Guo gave a novel master-slave system with force feedback [13]-[29]. But the master system needs some improvements.

Even if a small displacement occurs in the slave part, it will have a big impact on the results of surgeries. So it is important to confirm that the slave system could follow the master system well. Thus, a Fuzzy PID control is provided to decrease the tracking error. This paper improved the mechanical structure of the old master-slave system [13]. And experiments are designed to verify the dynamic performance of the system.

II. INTERVENTIONAL SURGERY ROBOTIC SYSTEM

In the minimally invasive interventional surgery, two motions, including the linear motion and the rotation motion, need to be applied to the guide wire. And these two motions could proceed at the same time.

So, a slave system need to be designed first, which can push and rotate the guide wire at the same time. Then a master system is needed which can be used by manipulator to simulate the linear motion and the rotation of the guide wire. The signals produced by the master system will be transmitted to the slave system to control it to finish the desired motion.

A master-slave system robot is presented in this paper to finish the required surgery motions. In this system, manipulators do the linear and rotations at the master side to simulate the operations doctors do in the surgery. Then the motion signals will be transmitted to the slave system through the control system. And the guide wire is driven by the signals to finish the motions required in a surgery. The slave system will measure the actual linear motion and rotation angle accurately in the movement by encoders in the linear sliding table servo motor and two EC brush less dc motors to achieve a closed-loop control of displacement. The force sensor in the slave system will measure the force at the proximal end of the guide wire and feed it to the manipulator through the force feedback device in master system to achieve a closed-loop control of force. Manipulators could be warned by this system in case the force between guide wire and vessel is too large to cause damage to human body. The overall system diagram is shown in the Fig.1.

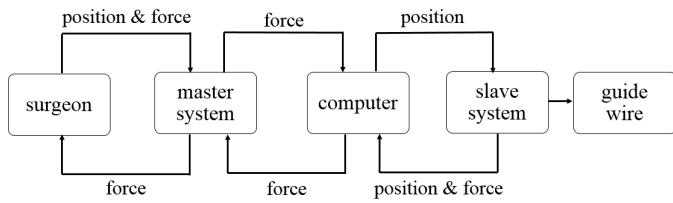


Fig.1 The Master-Slave System sketch map

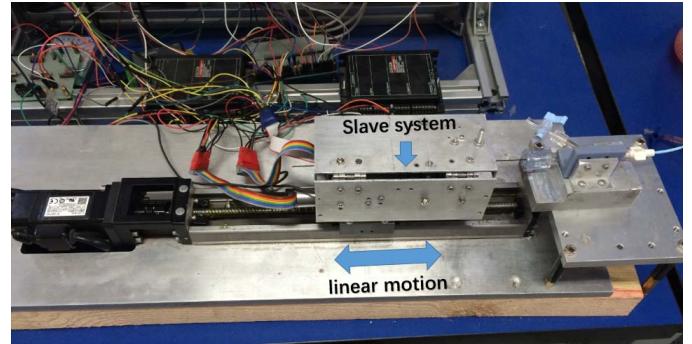
A. The slave system

The main purpose of the slave system is to finish the linear motion and the rotation while the guidewire is clamped. To ensure the two motions, the clamping force need to be large enough. Meanwhile, the clamping force should be controlled in a safe range to protect the surface of the guide wire. To complete this purpose, a clinical guide wire grasper is adopted in the slave system. The slave system is shown in Fig.2 (a) and Fig.2 (b).

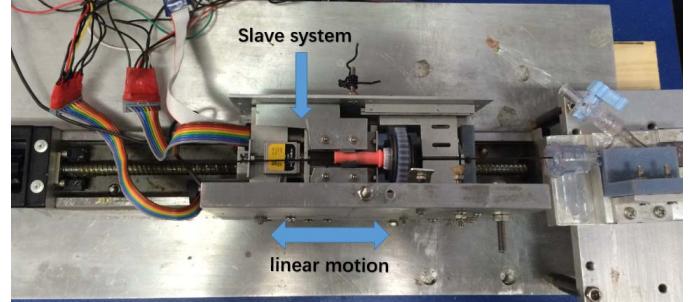
This system simulated doctors' operation in interventional surgery, which consists of three kinds of motions, the linear motion of the whole device, the rotation of the guide wire, and the clamping and relaxing of the guide wire. The slave system could push and rotate the guide wire with no mutual interference while the guide wire is clamped. When the guide wire is relaxed, the slave system could return to the original point without affecting the guide wire so as to get ready for next linear motion. The whole surgery process is consisted of couple times of clamping, pushing, rotating, relaxing and returning.

The basic rule, above all kinds of performance indicators, of a surgery robot is safety. This requires that the slave system will not cause damage to human body in a push process because of the large pushing force. Due to this reason, the

accurate measurement and the feedback to manipulator of the force between the guide wire and vessel is necessary. To get the accurate force, a force sensor is placed in the slave system. With this sensor, the force in the proximal end of the guide wire could be measured and transmitted to the master system through the control system to make manipulator feel the force. The control system also set a safety threshold to protect human body from the probable large force between the guide wire and vessel.



(a) The front view of the slave system



(b) The top view of the slave system

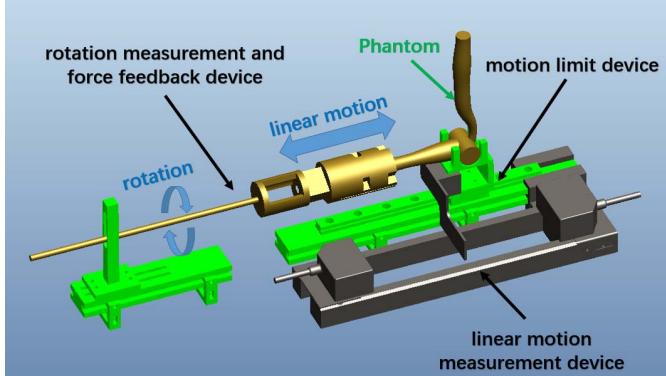
Fig.2 The slave system

B. The master system

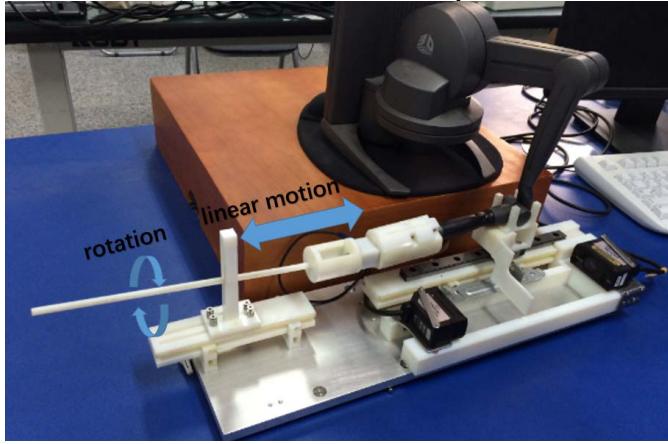
The master system is placed far away from the slave system to protect manipulators from the radiation. So, it is the only part manipulators could touch. And this requires that it should be convenient for manipulators to simulate the linear motion and the rotation of the guide wire through the master system while feeling the force on the proximal end of guidewire. So that both the required guide wire motion and the safety of patient could be ensured. In other words, there are three functions that master system should have, measurement of linear motion, measurement of rotation and force feedback. Basing on these three requirements, a master system which consists of three parts is designed. It is shown in Fig.3 (a) and Fig.3 (b). The brown part is rotation measurement and force feedback device. The black part is linear motion measurement device. The green part is motion limit device.

During the operating process, the required clinical motions are simulated by manipulators through pushing and rotating the operating arm. At the same time, the displacement of the operating arm is measured by the laser range finders and the rotation angle is measured by the Phantom. Also, the measured force in the slave system is fed back to manipulators

through the Phantom and the operating arm. Then the three functions required are completed.



(a) The 3D model of the master system



(b) The master system

Fig.3 The master system

A. Rotation measurement and force feedback device

The rotation angle measuring function and the force producing function of the Phantom are adopted by this part. An operating arm is fixed on the Phantom to simulate the clinical guide wire grasper. While manipulators rotating the operating arm, the rotation angle is measured by the Phantom. And the motion signal is transmitted to the slave system through the control system. So that the guide wire could be rotated by the slave system with the same angle. Also, a force sensor is fixed between the operating arm and the Phantom. The actual feedback force is measured by this sensor. And the force signal is transmitted to the control system to achieve a closed-loop control system of force feedback. The exploded view of this part's 3D model is shown in Fig.4.

B. Linear motion measurement device

According to the past experiments, although the linear displacement could be measured by the Phantom, the sample rate of the Phantom is not high enough to get good motion signals. This causes some problems on controlling the slave system. So, two laser range finders are adopted to measure the linear displacement. The exploded view of the 3D model is shown in Fig.5.

In this part, a baffle is fixed to the Phantom and two laser range finders are fixed to the base of the master system. The accurate linear displacement is measured by the laser range finders while the baffle moves following the Phantom. and the

motion signal is transmitted to the slave system through the control system. So that the guide wire could be pushed by the slave system with the same displacement. Also, the actual displacement of the slave system is measured by the motion encoder. And the signal is fed back to the control system to achieve a closed-loop control system of linear motion.

C. Motion limit device

The Phantom has 6Dofs, but only 2Dofs are needed in the master system. The extra 4Dofs will cause unnecessary motions that affects the measurement. To ensure the linear motion direction and the measuring accuracy of laser range finders, this part is designed as shown in Fig.6.

A limit block is designed to fix the Phantom on the slide. And the slide is fixed to the base. The operating arm is placed in another limit block. So that, the master system is limited to 2Dofs, linear motion and rotation.

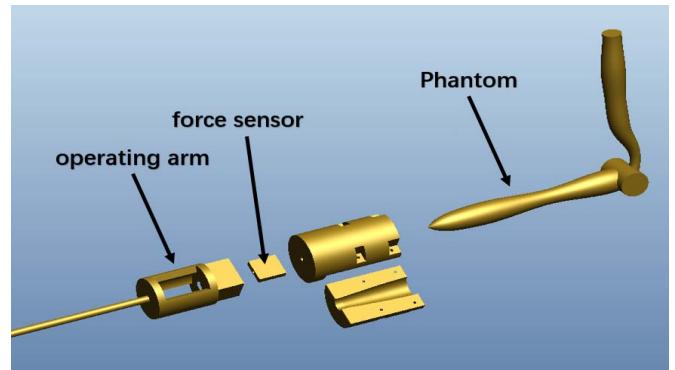


Fig.4 The exploded view of the rotation measurement and force feedback device's 3D model

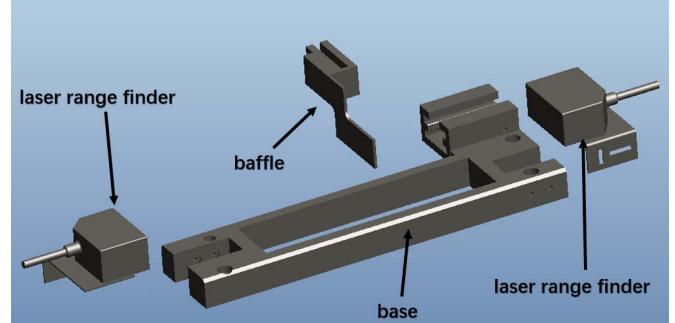


Fig.5 The exploded view of the linear motion measurement device's 3D model

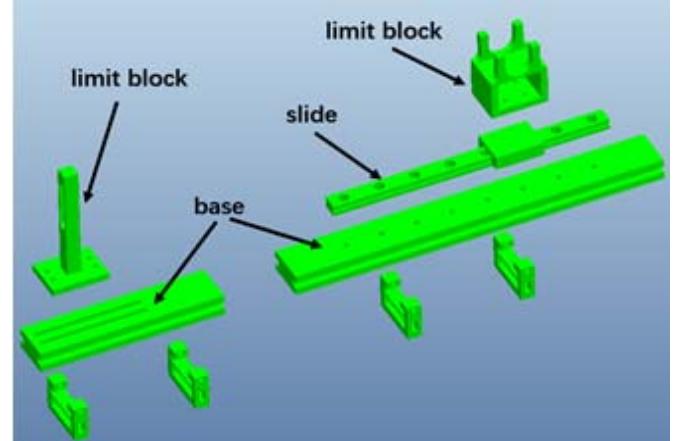


Fig.6 The exploded view of the motion limit device's 3D model

III. EXPERIMENTAL RESULTS

To verify the dynamic performance of the master-slave system robot, following experiment is designed.

A. Push the operating arm for about 5cm and then pull it back. The process is finished in about 10 seconds with constant speed. And the process is repeated for three times. In the whole process, the force feedback function is on. The displacement curves of master system and slave system are compared. The result is shown in Fig.7.

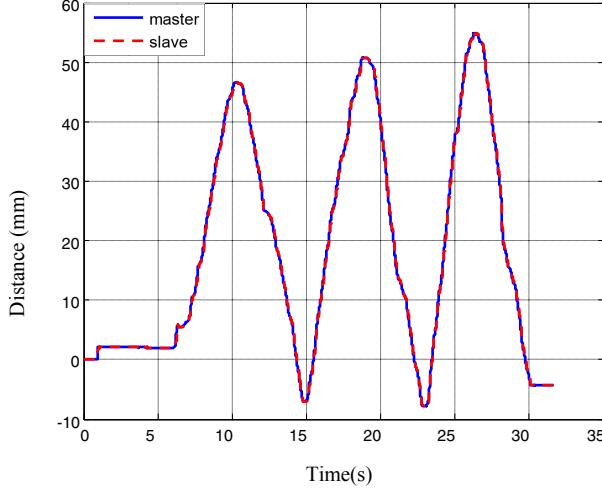


Fig.7 Displacement curves of master system and slave system with force feedback

The result shows that the slave system follows the master system well.

Then first wave crest from about 10s to 11s is amplified. The experimental result is shown in Fig.8.

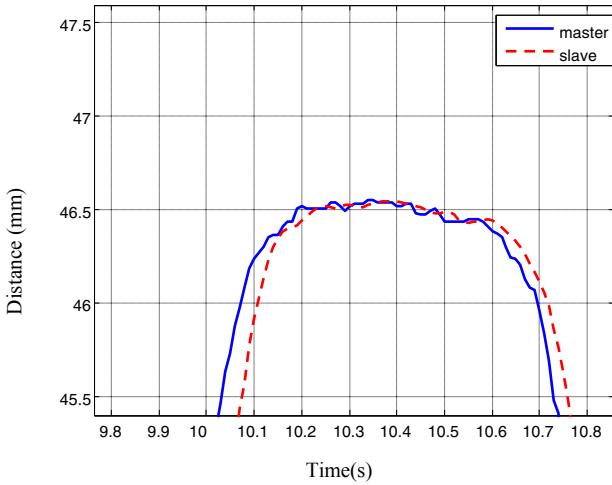


Fig.8 Amplification of the wave crest with force feedback

Slight shake occurs in the wave crest. And the slave system slightly lags behind the master system. But the lag time is small enough to reach the requirements of the surgery.

B. Push the operating arm for about 5cm and then pull it back. The process is finished in about 10 seconds with constant speed. And the process is repeated for three times. In the whole process, the force feedback function is off. The displacement curves of master system and slave system are compared. The result is shown in Fig.9.

The result shows that the slave system follows the master system well.

Then first wave crest from about 7.2s to 8s is amplified. The experimental result is shown in Fig.10.

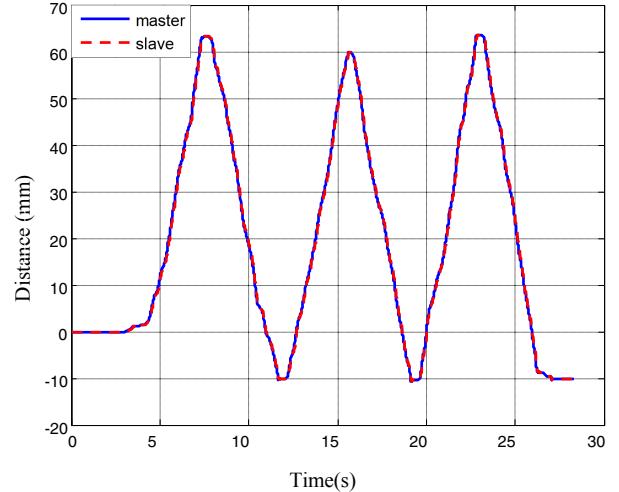


Fig.9 Displacement curves of master system and slave system without force feedback

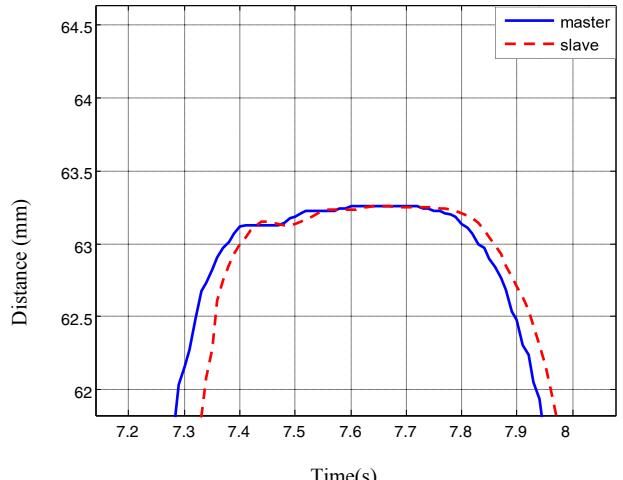


Fig.10 Amplification of the wave crest without force feedback

The wave crest is smooth. And the slave system slightly lags behind the master system. But the lag time is small enough to reach the requirements of the surgery.

The master-slave system robot is proved to be well behaved by the experimental results. The error is small enough, which is smaller than 1mm, to reach the requirements of interventional surgery.

But by comparing Fig.8 with Fig.10, it's clear to see slight shakes in the wave crest when the force feedback is on. It's hard to confirm what influence it has on the surgery. So there are still some improvements need to be achieved.

IV. CONCLUSIONS

An improved master-slave interventional surgery robotic system with force feedback is designed in this paper. The mechanical structure of the master side is improved. Now it has only 2Dofs. And it consists of three parts. And the guide wire could be pushed and rotated accurately by the slave side.

Experiments are designed to verify the performance of the whole system. And the system is proved to be well behaved to reach the requirements of minimally invasive interventional surgery. However slight shake occurs in the crest wave when the force feedback is on. The influence is not clear now. So developments are needed to improve the mechanical structure. In conclusion, this master-slave system is an experimental operating device for the current catheter interventional surgery. And it has great value of training.

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