

# The Evaluation of a Novel Force Feedback Interventional Surgery Robotic System

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**Abstract** - The interventional therapy is a kind of minimally invasive treatment. Under the guidance of medical imaging equipment, surgeons take the special catheter, guide wire and other precision instruments import in the body to do the pathological diagnosis and local treatment. The characters of interventional therapy are no operation, small trauma, rapid recovery, etc. However, the interventional treatment has some shortage such as hard to measure the front collision force of the guide wire, and the harm of the X-rays to surgeon. Above those shortages, this paper use the phantom desktop as the master controller, and design a new novel of interventional operation slave system which has force feedback structures. Besides according to the master-slave motion results, the paper has done the system identification. Then the system uses MRAC fuzzy PID looped control. Finally, this paper analyses the dynamic performance of the surgery robot system and makes a comparison between the simulation and the real results.

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

## I. INTRODUCTION

Minimally invasive interventional surgery has many 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 and cardiovascular diseases [1]. However, currently the invasive interventional surgery has some deficiencies: 1) Surgeons need to work long hours under X-ray, and so the surgeon is under the radiation, which will do harm to their health. 2) The surgeons need rich knowledge and many years of operating experience of heart and head blood-vessel to avoid making mistakes during the surgeries. 3) The surgeon's wrong operation easily leads to a perforation, and it will cause the failure of surgery. This mistake will endanger patient health, even the life. Nowadays, with the development of robot technology, there is an effective way to solve this problem by combining robot technology and the integration of vascular interventional technique [2].

In the past few years, some products have been developed. Catheter Robotic Inc. produced a remote catheter system called Amigo [3]. This system has a handle to control the catheter and a slave system to control the catheter. It can control the catheter to do the rotation, push and front tip bending. And one of the earliest products is a robotic catheter placement system which is called Sensei X Robotic Catheter

System supplied by Hansen Medical [4]. This System provides the surgeons the Artisan Extend with advanced ability of guidance and the ability of deformation under control. It has manipulation platform for the surgeons out of the operation room, and also the slave system of the surgery in the room. Therefore, it can allow for more precise manipulation with less radiation exposure to the doctor. Magnatecs Inc. produced their 'Catheter Guidance Control and Imaging' (CGCI) system [5]. The Stereotaxis Inc. developed a magnetic navigation system called the Stereotaxis Niobe [6]. This system has 4 large magnets placed around the table, which are customised catheters containing magnets in the tip. The catheter is moved by the magnetic fields and it is controlled at a nearby work station. 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 of these products. Most of them aren't suitable for the surgeons to operate, for those products don't design according to the manipulation of surgeons. The size 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 and it is quite difficult to equip such a little sensor on the catheter of guide wire. Lastly, they can only measure their force feedback at the end of 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. The existing system can only do the motion as the surgeons manipulate the device out of the surgery room.

Recently, many experts pay attention to the force feedback to the surgeons to enhance the feeling of remote-controlling. Shu-xiang Guo put forward a novel robot system, the system uses a master-slave control mode and it achieves the remote operation between Japan and China [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

[10,11]. Hedyeh Rafii-Tari and Jindong Liu tried to use the image to design a learning-based model [12]. This study enables the catheter to do the semi-automatic motion in the vascular. According to these products and researches, this paper designed a novel interventional surgery system. This system uses the master-slave mode. In order to verify the accuracy and stability, the system identification has been done and the best result has been taken. Next, the force feedback system has been detected in order to confirm its accuracy. Then, the fuzzy PID controller has been chosen for this system. Finally, this paper has given the real results and the simulation results.

## II. INTERVENTIONAL SURGERY ROBOT SYSTEM

The interventional surgery robot system consists of two parts, the master controlling platform and the slave system. The master platform is the control part of the robot system for surgery, and the slave system is the control part of the guide wire or the catheter. In this interventional operation system, the surgeons do the surgery from the master side by using a phantom desktop 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 system is similar to the manipulation that surgeons use the guide wire or catheter to do the interventional surgery. By this method, the system ensures the consistency of the master-slave system movement. The master platform Phantom desktop communicates with the computer by Ethernet, and the slave system communicates with the computer through PCI bus protocol. The overall system diagram is as shown in Fig.1.

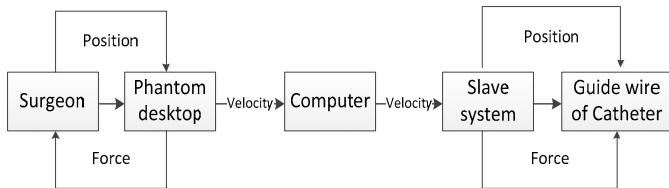


Fig.1 The master-slave system sketch map

### A. The slave system

The slave system is shown in Fig.2 this part is placed in the operating room. Surgeons manipulate the master side remotely and the slave system will do the similar motion. 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 controlling the guide wire if it is clamped or relaxed. In this paper, a highly realistic vessel model was used to replace the real surgery environment.

As it shown in Fig.2, the slave system is put in the surgery room. Its motion is just similar to what the surgeons do. When the surgeons need to manipulate the guide wire or catheter, this structure will clamp them. Then this system can manipulate the guide wire or the catheter to do the linear

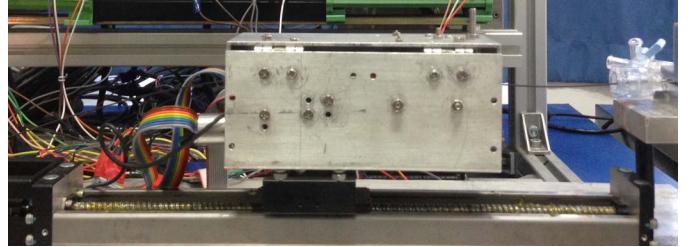


Fig.2 The slave system of the surgery robot system

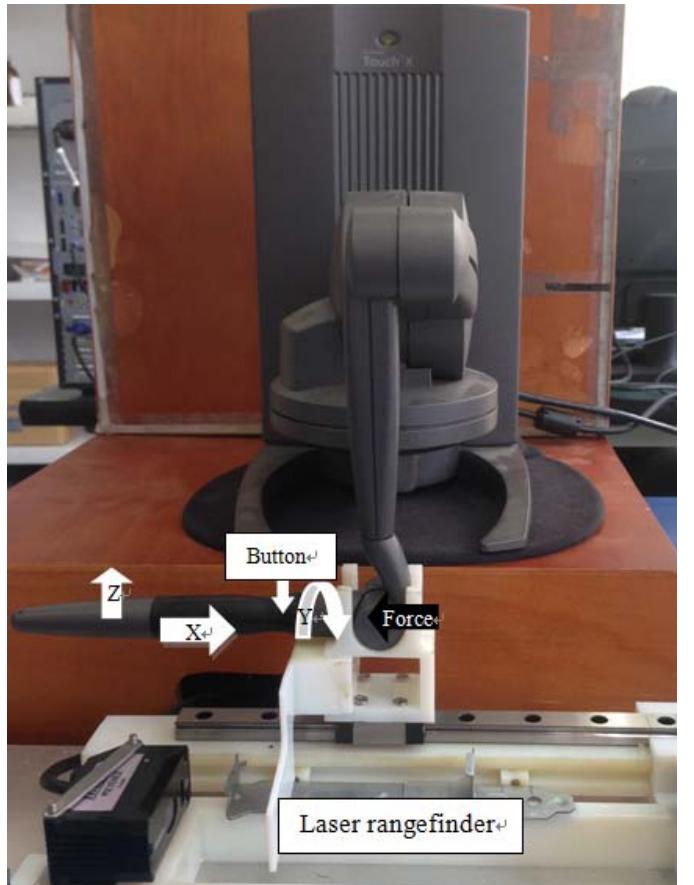


Fig.3 The master platform manipulated by the surgeons, three axes and a button to control the slave system, force feedback on the X axis

motion or rotation motion. For the linear guideway on the slave system has critical distance, the surgeons need to withdraw the slave system. This motion of slave system is similar to what the surgeons really do in the surgery. The system will relax the guide wire or catheter. Then the structure can withdraw without controlling the guide wire or catheter.

### B. The master system

In order to achieve the remote control, this paper uses the phantom desktop as the master platform. To achieve high precision, the laser rangefinder was equipped in the master system. The system is shown in Fig.3.

As Fig.3 shows, the master side has three axes to control the slave system. The X axis is used to control the linear motion. When the surgeons need to manipulate the guide wire or catheter to go forward, firstly push the button on the handle,

and the slave system will clamp the guide wire; secondly manipulate the handle go forward along the X axis, and the slave system will also clamp the guide wire or catheter to go forward. When the surgeons need to manipulate the guide wire or catheter to do the rotation motion, the first step is the same as what the surgeons do in the linear motion; secondly the surgeons can manipulate the Y axis to do the rotation motion. Moreover, the function of Z axis is to confirm if the surgeons want do the clockwise or anticlockwise rotation motion. When the surgeons put down the Z axis, the slave system will control the guide wire or catheter to do the clockwise rotation motion, and when the surgeons put up the Z axis, the slave system will control them to do the anticlockwise rotation motion. When the surgeons need to manipulate the slave system to do the withdrawing motion, they can put button down again, and ensure that the slave system has relaxed the guide wire or catheter. Then the surgeons can manipulate the handle to do the linear motion and go back to the suitable position. The other improvement in this system is the laser rangefinder, with this device the system can ensure a high accuracy.

This section introduces the master and the slave system of the surgery robot system. For this system is very complex, before choosing the suitable controller, the system identification must be done at first. It will be introduce in the next section.

### III THE IDENTIFICATION OF THE SYSTEM

The identification of the system uses the input function and the output function to determine the mathematical models which describe the behaviour of the system [13]. In this system, for the complex mechanical structure and the controlling condition the fuzzy identification of the system has been used. The fuzzy identification has such good characters to identify the complex structure system and to identify the human beings controller. The T-S [14] model has been used in the identification. It points at the practical linearization. The advantages of this method are the brief structure and the high approach ability. According to our experience, some experiments and the last research [15] about this system, the speed is the crucial factor which influences the controlling consequence. So the experiments of the system identification are designed according to a move step in a sampling period. The sampling period is set at 5 milliseconds. The linear motion system and the rotation motion system are different, so the different identification has been made. In the linear motion system, the motion ranges from 0.1 mm to 1.0 mm, and in order to know the limit of this system, two high-level motion steps have been made in the experiment. One is 1.5 mm per period, and the other is 2.0 mm per period. When the motion step is about 2.0 mm per period, the velocity is 0.4 m/s. In the research [16] by Johansen.T, this speed is considered to be very high. It is the same in our system. Besides the linear motion system, the rotation motion system also needs to be considered. The rotation motion ranges from 10 degrees to 100 degrees. Also, in order to know the extreme condition of the rotation system, a high-level motion has also been done. It is about 150 degrees. In the minimally interventional surgery, the rotation motion has relatively high accuracy and low

speed. So the rotation motion step about 150 degrees is quite enough to identify the system. Moreover, except using these results to do the identification of the system, the force feedback system should also be examined to ensure that the force feedback will not be affected by the linear motion or rotation motion. It can only be affected by the force from the guide wire or catheter. So the results of this section can be divided into three parts, the linear motion system identification, the rotation motion system identification and the detection of the force feedback system.

#### A. The identification of the linear motion system

The fuzzy identification has been done for this linear motion system. For each motion step, the step-response method and the least square method are used to calculate the system parameters. According to the characters of this system, the system was considered to be a second-order-system or a second-order-delay-system. The system identification tool in the MATLAB R2013a has been used to do these experiments. The results of these three models have been shown in Fig.4, Fig.5.

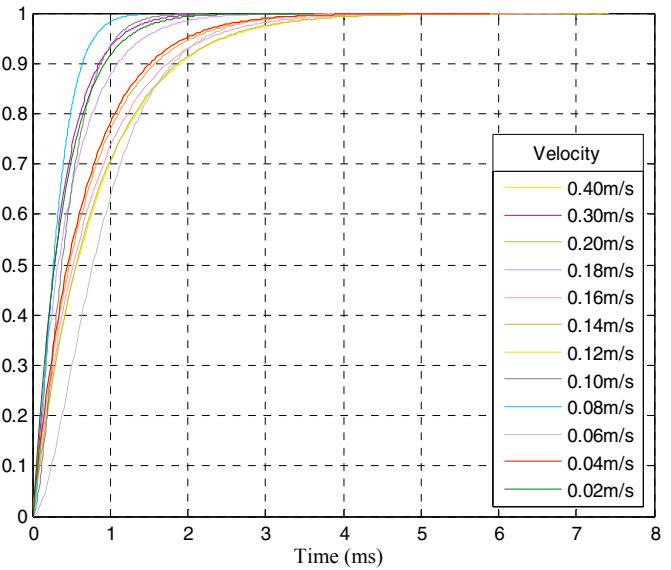


Fig.4 The step response of the second-order-system (linear system)

According to these three results, the second-order-system is the best results. The second-order-delay-system has very bad results of the step response examination. So choose the second-order-system as the results. The Eq. (1) as below is the second-order-system. And for the simulation results are the continuous system results, the Laplace equation should be changed into Z-transform in the discrete system. The parameters of the second-order-system are shown in the TABLE.I.

$$G(s) = \frac{Kp1}{(1+Tp1*s)(1+Tp2*s)} \quad (1)$$

From the TABLE.I the conclusion is that the Kp1 of this system is about 1. However the parameters of Tp1 and Tp2 will change in different velocity. So the designing standard of fuzzy controller depends on the velocity.

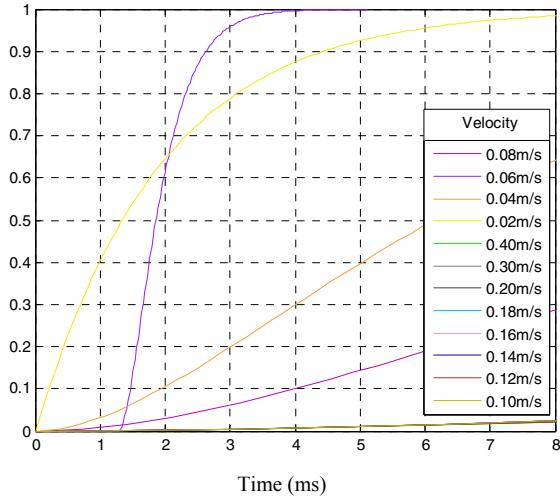


Fig.5 The step response of the second-order-delay-system (linear system)

TABLE I  
The parameters of the second-order-system (linear system)

Velocity(m/s)	Kp1	Tp1	Tp2
0.02	0.99975	4.0256e-4	1.2885e-7
0.04	0.99975	6.5648e-4	1.4139e-7
0.06	1	4.6478e-4	4.6471e-4
0.08	1.0001	1.3045e-4	1.9962e-4
0.10	1	2.2652e-4	2.2652e-4
0.12	1	6.5708e-4	1.2317e-7
0.14	1.0001	6.8668e-4	4.1175e-9
0.16	1	7.5635e-4	1.2678e-7
0.18	1	1.0000e-6	4.7815e-4
0.20	1	8.1585e-4	1.5281e-9
0.30	1	3.6079e-4	3.0608e-5
0.40	0.99997	8.2633e-4	1.1075e-8

### B. The identification of the rotation motion system

According to the model of the linear motion system, the rotation motion system was considered as a second-order-system. The simulation results are shown in Fig.6. So the equation is the same as the linear motion system like Eq. (1). The parameters are shown in TABLE.II. It is not hard to find that when the angular velocity is too high just as  $4.0^{\circ}/\text{ms}$ , the system step simulation will be out of control. However, in our system  $3.0^{\circ}/\text{ms}$  has been enough for the surgery. So in order to ensure the security and accuracy of this system, the fuzzy controller with a threshold value has been designed to solve this problem.

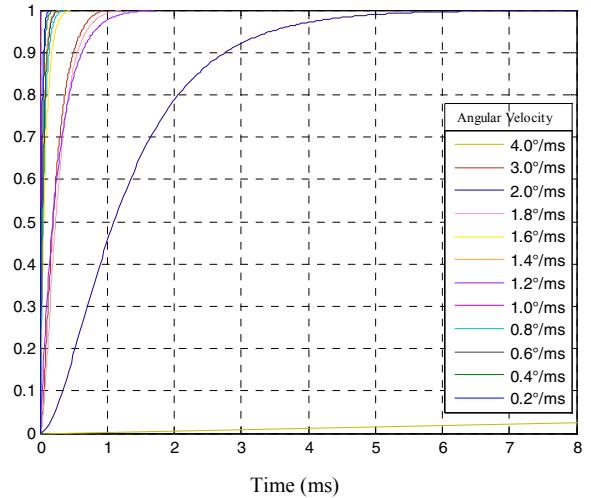


Fig.6 The step response of the second-order-system (rotation system)

TABLE II  
The parameters of the second-order-system (rotation system)

palstance ( $^{\circ}/\text{ms}$ )	Kp1	Tp1	Tp2
0.02	1.0006	2.3281e-5	5.8257e-7
0.04	1.0011	2.9957e-5	4.5673e-7
0.06	1.0013	4.6986e-5	1.7331e-6
0.08	1.0009	2.2010e-7	5.7246e-5
0.10	1.0015	6.8413e-7	2.5297e-7
0.12	1.0019	2.7300e-4	2.6283e-7
0.14	1.0010	4.4447e-5	4.1291e-7
0.16	1.0018	7.6898e-5	1.2607e-6
0.18	1.0024	9.5033e-5	1.8955e-4
0.20	1.0000	3.8544e-4	9.8914e-4
0.30	1.0115	1.9862e-4	5.1680e-5
0.40	1.8216e+6	5.5178e+5	2.8306e-3

All of the simulation results use the step-response method to calculate, and the simulation results were iterated by the least square method.

### C. The detection of the force feedback system

As mentioned before, this minimally interventional robot system has a force feedback system. So to ensure this force detection system is effective, if the high linear velocity or the angular velocity will influence the force detection results needs to concern. The average force was calculated during step motion. The results are shown in Fig.7 and Fig.8. The results showed that although the results have a high zero drift, so the moving average has been used.

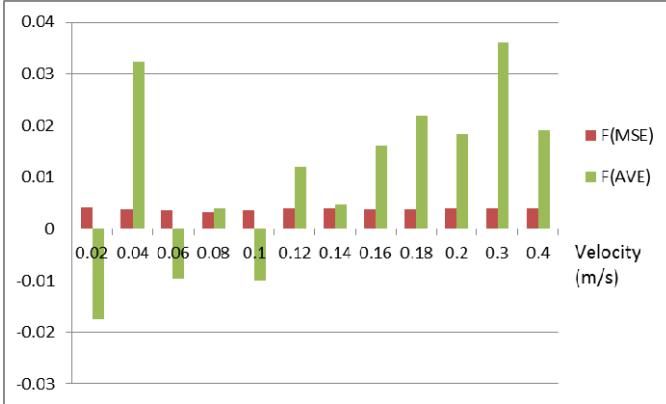


Fig.7 The force detection results during the linear motion

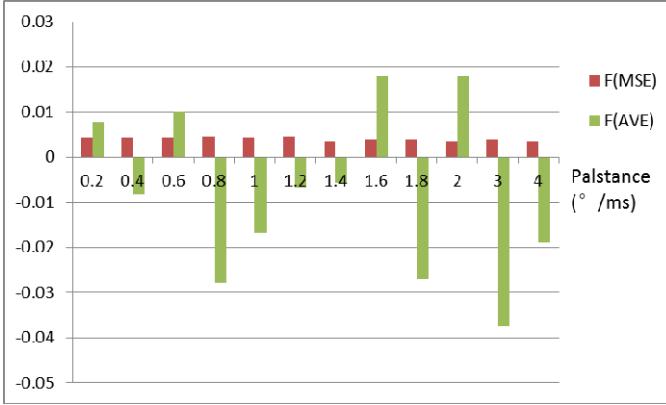


Fig.8 The force detection results during the rotation motion

There is no relationship between the force feedback and the motion condition. And the force feedback of the guide wire or the catheter ranges of 1 N. So the force feedback system is effective in this minimally interventional system.

Obviously, There is still a problem that if there is a saltation of force when the velocity or the palstance suddenly changes. However, this paper aims at if the system has stable performance in position control and force detection in a long term. Based on the results above, the system is considered to be feasible. And according to the results in this section, the system transfer function has been calculated and the force detection is relatively stable. So in the next section, the fuzzy PID controller has been designed according to the results of the system identification.

#### IV THE CONTROL METHOD AND THE RESULTS

According to the section III, a fuzzy PID controller was designed. Yan qing. Peng has proposed a controlling method about Model-reference PID control [17]. On the basis of the characters of our system, the MRAC Fuzzy PID control was chosen [18]. Although this method is good enough in controlling this complex system, the problem still exists. For this system needs to do a continuous motion during the whole surgery, the velocity is not the same as the step response. So every motion per period was considered as a step motion, and the velocity was used as the factors to choose the suitable reference model. After the error was calculated between the reference system and the real results after fuzzy PID control

and the error between the reference model and the input was calculated. Besides use the velocity to change the PID parameters in fuzzy PID controller, the error between reference model and real system output after fuzzy PID control and the input is chosen as a judgment data of fuzzy PID controller. And the control flow chart is as Fig.9. The linear motion system control is similar to the rotation motion system control, so they have the same control flow chart but different parameters and reference model.

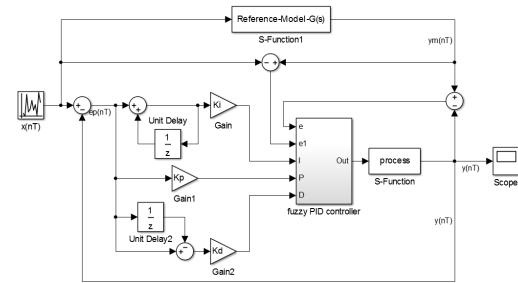


Fig.9 The MRAC fuzzy PID control flow chart

The derivation of the control method is as below. First, according to the input  $x(nT)$  and the sampling time, the velocity and the angular velocity  $v(nT)$  can be calculated. The Eq. (2) shows this relationship. This is a judgment factor for the fuzzy PID controller and also for identifying the reference model  $G(s)$ . The reference model  $G(s)$  is the Eq. (1). The parameters of the model are in the TABLE.I and TABLE.II.

$$v(nT) = x(nT) / T \quad (2)$$

$$v(nT) \rightarrow G(s)$$

After get the model  $G(s)$  in Eq. (1), the reference output  $ym(nT)$  is calculated by Eq. (3).

$$ym(nT) = (Kp1)x(nT) - (Tp1 + Tp2)((n-1)T) - y((n-2)T)(Tp1 * Tp2) \quad (3)$$

Then the error  $ep(nT)$ ,  $e1(nT)$ ,  $e(nT)$  is calculated by the Eq. (4).

$$ep(nT) = y(nT) - x(nT) \quad (4)$$

$$e1(nT) = ym(nT) - x(nT)$$

$$e(nT) = ym(nT) - y(nT)$$

After getting the Eq.(4), the Eq(5) can be transformed from the Eq.(4).

$$ep(nT) = e1(nT) - e(nT) \quad (5)$$

In order to get the final output  $y(nT)$ , backward difference has been done to the error  $e1(nT)$ ,  $e(nT)$ , and the error  $ep(nT)$  needs to be as small as possible, so error  $e1(nT)$ ,  $e(nT)$  are considered to be the same. The backward differential equation of this algorithm is Eq. (6).

$$y(nT) = x(nT) + y((n-1)T) - x((n-1)T) - e1((n-1)T) + e((n-1)T) \quad (6)$$

This equation is enough for the closed-loop, for except the output  $y(nT)$ , each item is known. However, there is still a

fuzzy controller for this system, so we need to find the error  $e_p(nT)$  in this equation. The equation is changed into Eq. (7).

$$\begin{aligned} y(nT) &= x(nT) + y((n-1)T) - x((n-1)T) - K_e(e_p(nT) + e(nT)) + e((n-1)T) \quad (7) \\ e_l(n-1)T &= K_e(e(nT)) \end{aligned}$$

As mentioned before, the error  $e_l(nT)$ ,  $e(nT)$  is considered to be the same, so the Eq. (7) could be the Eq. (8).

$$y(nT) = x(nT) + y((n-1)T) - x((n-1)T) - K_e(e_p(nT) + e(nT)) + e((n-1)T) \quad (8)$$

The items after the input  $x(nT)$  Eq. (8) can be converged as the formula. (9).

$$e_p((n-1)T) - e_l((n-1)T) + e((n-1)T) \quad (9)$$

Obviously, this formula conforms to the goals that make the error  $e_p(nT)$  approach to zero, so we consider this control method is convergent.

We use this control method in the surgery robotic system to do the experiments in the vessel model. The guide wire was used in the experiment. The begin position of the guide wire shows in Fig.10 and the end position of the guide wire shows in Fig.11.

The linear position tracking during the experiment shows in Fig.12, and the rotation position tracking during the experiment shows in Fig.13. The force feedback during the experiment is shown in Fig.14. From the results, the proposed MRAC fuzzy PID control is suitable in this surgery robotic system. Moreover the force feedback is reliable in this system. And for the force is not very big in this surgery, it will have little influence to the surgeons during the surgery.

The results shows a very good performance in the position tracking, however there is still problem in how to deal with the force feedback. First of all, there is a very big drifting during measure the force. Secondly, in the current system, the force feedback is used to let the surgeons know there is a feedback.

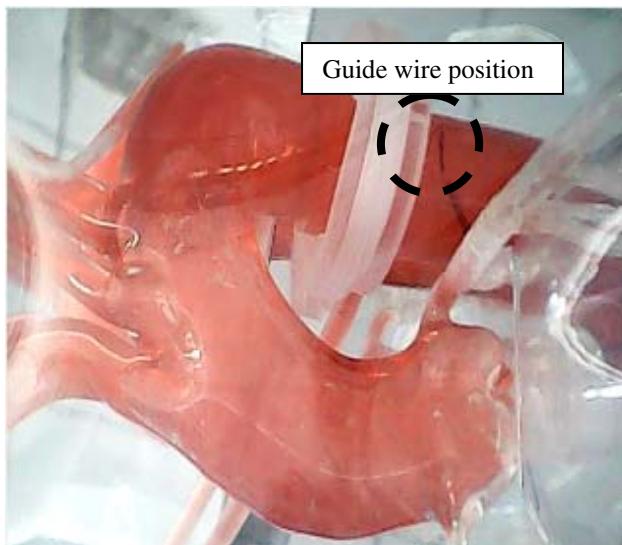


Fig.10 The begin position of the guide wire

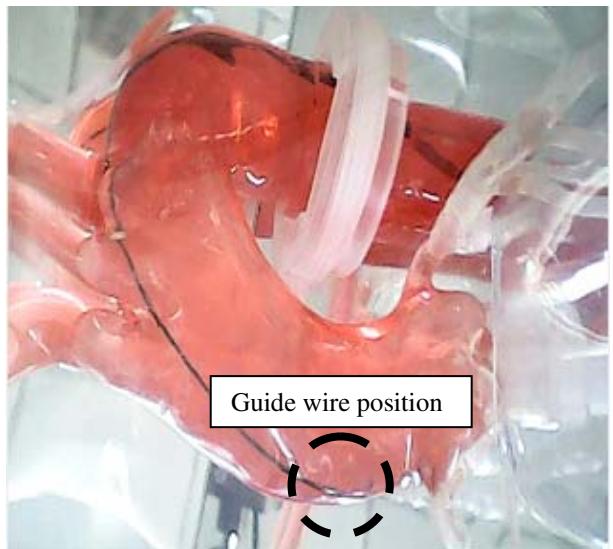


Fig.11 The end position of the guide wire

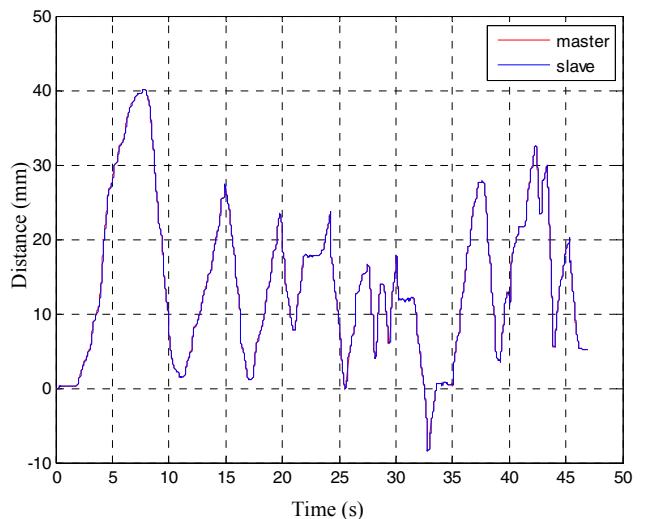


Fig.12 Linear position tracking of the master-slave system

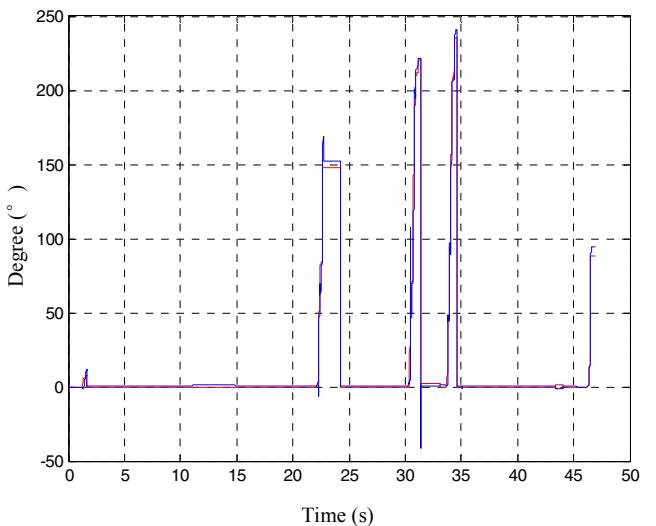


Fig.13 Rotation position tracking of the master-slave system

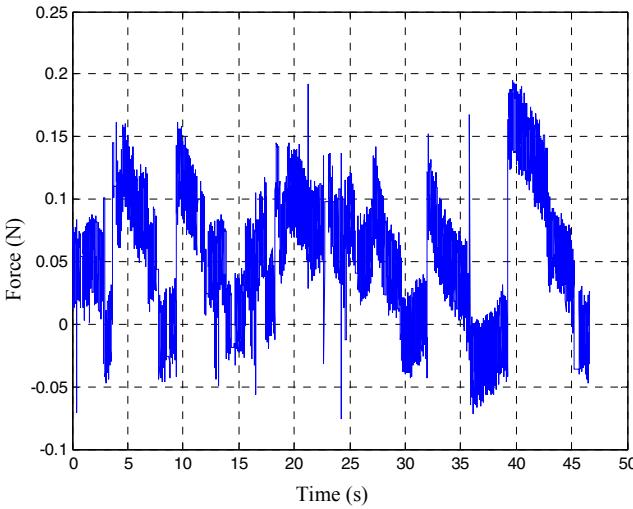


Fig.14 The force feedback during the whole experiment

## V CONCLUSIONS

This paper presented a novel force feedback interventional surgery robotic system, and the evaluation had been done for this system. First of all, the system identification has been done for the motion system of the surgery robotic system. Secondly, the force detection system has been verified that it is feasible. Thirdly, this paper made an improvement on the MRAC fuzzy PID control method for this system. Finally, the results from the experiments in the vessel model have verified the method and the system. The contribution of this paper is about the mechanical structure, the method of the evaluation in the complex system and the control method for this system. However, there are still some disadvantages in this system, first of all, it still needs to be verified when the velocity has a sudden change if the force detection is accurate. Moreover, besides the velocity, if the acceleration is useful for the MRAC fuzzy PID control. So there is still some study need to do for this system.

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