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A Study on Telecommunication Technology and Remote-control Algorithm in Minimally Invasive Surgical Robotic System

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***Abstract* - Minimally invasive surgery is commonly applied in cardiovascular diseases at present while surgeons exposed in the X-ray. With the development of automation and mechanism in ro botic system, robot-assisted surgery had been introduced to solve such trouble. And minimally invasive surgical robotic technology has developed rapidly. In this paper, we propose a remote-control algorithm based on a fuzzy adaptive PID control algorithm in MI S robotic system to realize the demand for remedy in remote distr icts. Meanwhile, such hybrid algorithm is proposed to reduce the environmental interference and remove the effect of time-delay in signal transmission of remote operations. The results of simulatio n and experiments validate that such algorithm actually suppresse s the interference of low frequency and improves the tracking per formance of the master-slave system.**

Index Terms - Minimally Invasive Surgery(MIS); Time Delay; Control Algorithm; Adaptive Fuzzy PID Control

I. INTRODUCTION

A. The Development of Minimally Invasive Surgical Robots

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 make 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 integration of 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. 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 [8]. Ganji set the heart radio-frequency ablation catheter navigation platform [9-12], and did the corresponding catheter experiment. RS Penning, D Glozman and RS Penning did some algorithms research in pipe robot system closed-loop

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control, those researches expect control catheter to the specified location [13-15]. 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 invasive 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 a hybrid algorithm based on Fuzzy PID control to decrease the tracking error.

B. The Development of The Remote-control Technology

For the remote surgery, there are some troubles remained to solve and many teams are still different controlling algorithm to overcome these problems. As is known to us, the telecommunication could be interfered by environmental noises and gives a time delay to message transforming. Such troubles affect the quality of the remote surgical system. Butner's research implied that the tolerance for time delay of the human tele-surgery is 300 ms[16]. And Wang Shuxin carried out a tele-operated minimally invasive laparoscopic surgical platform of which time delay for controlling signal transforming in single direction is 12.3 ms and time delay for whole operational process is 302.6ms[17].

To deal with the time delay and noise interference, Wang Hongmin conducted a research on controlling network time delay to compensate the noise disturbance induced by the environment and the 2-second time delay with the disturbance observer and the H∞ controlling algorithm[18].

In this paper, the algorithm for the time delay elimination and the removal of the disturbing noise will be proposed based on the adaptive fuzzy PID controller.

II. The Structure of The MIS Robotic System

Minimally invasive surgical robotic system structure consists of two parts—master side and slave side. The master side is the controller of the robot system for surgical operation, and the slave system controls the part of the guide wire. In this invasive surgical system, the surgeons 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 in which doctors use the guide wire to do the minimally invasive surgery, which ensures the consistency of 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 which would be developed with LAN for the first step in future work. 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 precisely through the encoder and transmitted by the PMAC motion control card 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 aspect of controller selection, the system adopts the way of fuzzy PID control because of the complexity of the master-slave system and the uncertainty of operating factors. This control mode guarantees the accuracy of the slow motion and fast motion at the same time.

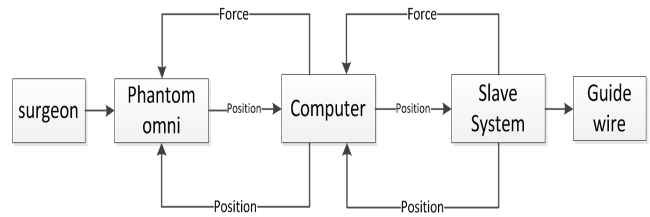

Fig.1 The Master-Slave System sketch map.

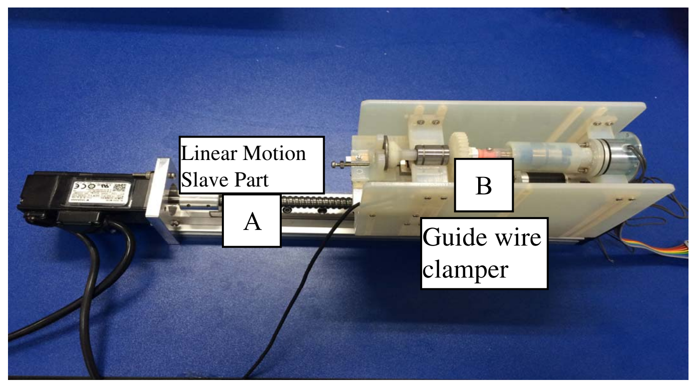

Fig.2 The front view of the improved slave system.

A. The Slave System

The slave system is shown in Fig.2, this part is placed in the operating room, and surgeons use the master side remotely to realize the manipulation of surgery. 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. In this paper, we use an EVE model to replace the real environment. The EVE model is shown in Fig.3.

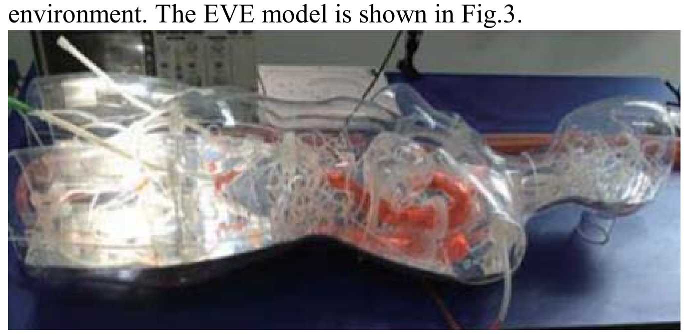

Fig.3 The EVE model.

As is shown in the Fig.2, 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 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 which it 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.

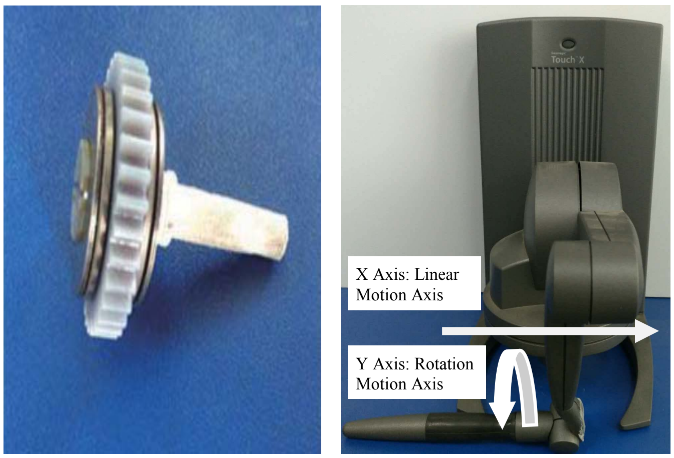

Fig.4 The device of the guide wire reversing device and the phantom.

(a) is the guide wire reversing device, (b) is the phantom omni.

Next 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(a).) 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 axis 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 guide wire 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.

B. *The Master System*

The master part is a phantom omni (shown in Fig.4(b).). 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 this master part to achieve the purpose of controlling the slave system. When rotating handles, the guide wire will follow the movements of the guide wire reversing device as shown in Fig.4, and when the handles on the X axis precession movement, the slave structure which is on the linear slide will do forward and backward movement in order to achieve the goal of accurate motion of master-slave coordination. In the experiment of using the phantom omni, in order to achieve better test effect, ensuring the accuracy and the safety of the operation process, the motion data will do a filtering processing in the software during the movement, and with joined a filter, the movement process of precision and accuracy are improved significantly. At the same time, it is important to say that the force will feedback to the master side, thus, the force of the master side will affect the motion status, so in order to keep the safety and accuracy, we need to use appropriate controller for this system. And we choose the Fuzzy PID controller for the whole system.

III. The Controlling Method

A. *The Design of Adaptive Fuzzy PID Control Algorithm*

In remote catheter intervention surgery system, it is better to use Fuzzy PID closed-loop control [19]. Because we need to change very fluently and quickly between the fast motion with low precision and slow motion with high precision, so the parameters are quite different, and the strategy is different to control in these two conditions. According to the characteristics of this system we designed different strategies, and the controller block diagram as shown in the Fig.5.

According to input of the error e and error change rate De 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 parameters are depended on the speed of surgeon's hand. Because the system would never know the next step of the motion, the parameters of the system are hard to choose. However, 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, then we chose the appropriate parameter from the table.

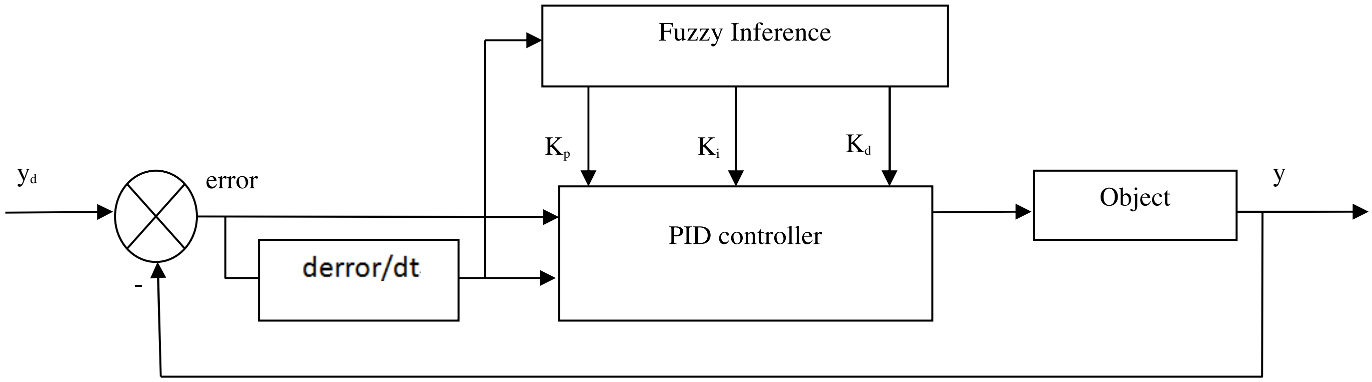

Fig.5 The Fuzzy Adaptive Controller

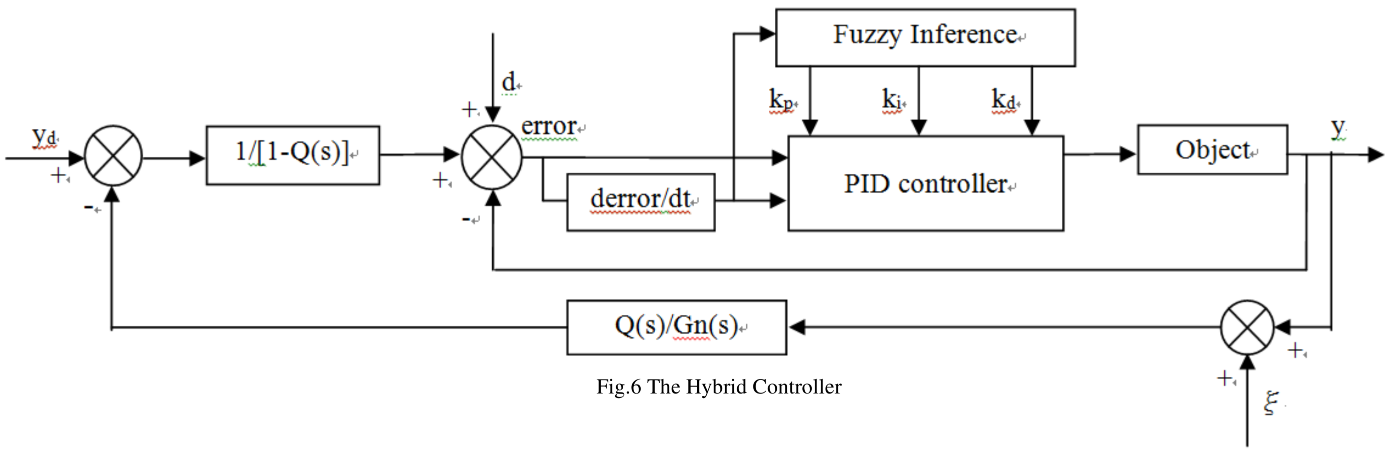

Fig.6 The Hybrid Controller

B. The Design of Hybrid Algorithm for the System

For the other two problems, which are time delay and the noise disturbance, we introduced a disturbance observer into the Adaptive Fuzzy PID control algorithm. And the control flow chart is shown in Fig.6.

Based on the adaptive fuzzy PID control, the hybrid algorithm adopts the inverse function of the transfer function which is tuned by fuzzy inference. And then, the low-pass filter Q(s) is designed to filter the noise and disturbance of low frequency, which accomplish the aim of eliminating the environmental disturbance and the inverse function $G_n(s)$ is a nominal model of the fuzzy self-tuned transfer function. Meanwhile, the output delay observer is applied to improve the tracking performance of the system.

IV. The Results of Simulation And Experiments

A. The Experimental Result of Adaptive Fuzzy PID 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. At the same time, when we control the phantom omni to do the straight linear motion, part B as shown in Fig.2 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 analyse the result of slow motion and the fast motion.

Fig.7 and Fig.8 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.7 and the Fig.8 also show the performance of the system in low speed. The results indicate that the system is relatively stable when doing this motion. Fig.9 and Fig.10 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.

B. The Simulation of The Proposed Algorithm

In order to verify the function of the proposed algorithm, simulations for both the time-delay observer control and the nominal-model-based control are simulated by the Simulink of the MATLAB.

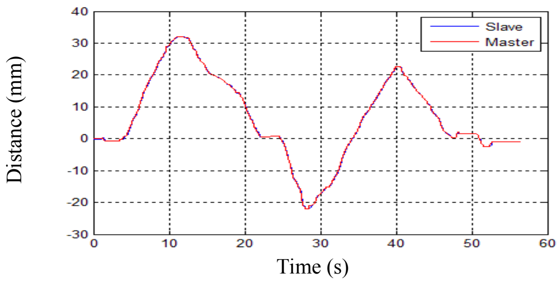

Fig.7 Position tracking of the master-slave system.

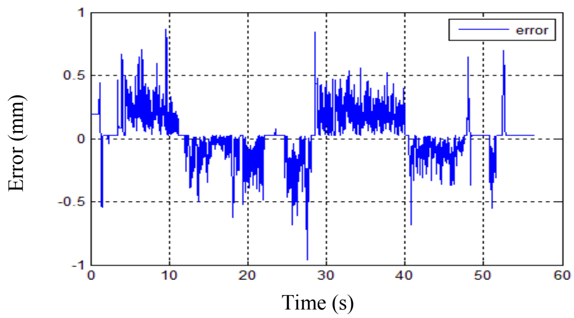

Fig.8 The tracking error of the master-slave system.

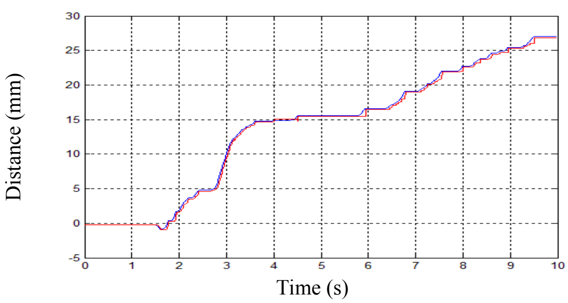

Fig.9 Position tracking of the master-slave system (high speed).

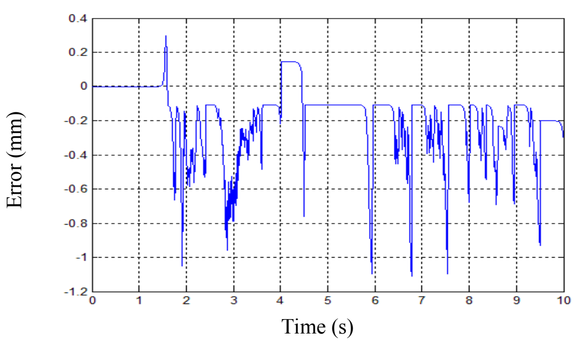

Fig.10 The tracking error of the master-slave system (high speed).

For the test for time-delay removing, the command signal for input is set as 3 seconds later than the original one, which is shown in Fig.11. When giving the command signal into the hybrid controlling system, the position and speed tracking performances are demonstrated in the Fig.12. And the error of position and speed tracking is reducing to zero in 10 seconds, which is shown in Fig.13.

For the aspect of the nominal-model-based observer, we simulate the system with and without the observer to verify the impact on the tracking performance of noise eliminating brought by the environmental disturbance. From the simulation result, it can be estimated that the maximum error of the system with observer is properly 0.1mm and the maximum error of the system without the observer is approximately 0.05mm which is much smaller. The above results are shown in Fig.14.

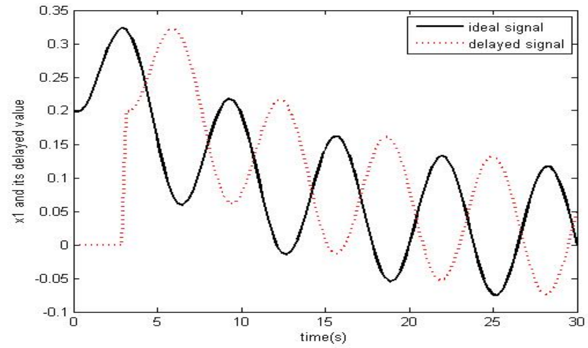

Fig.11 The input signal and the delayed signal.

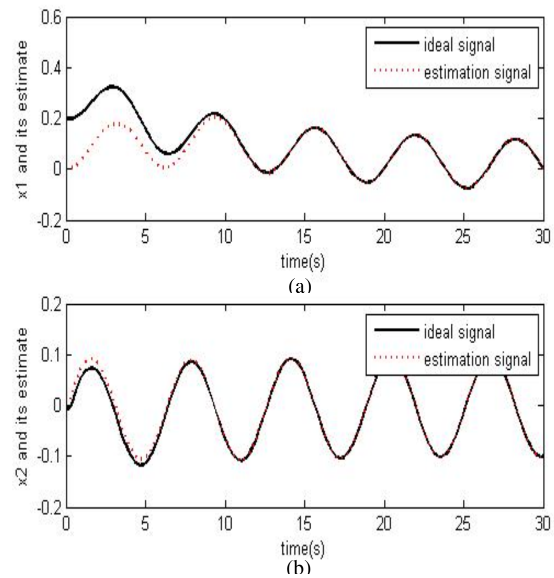

Fig.12 The simulation results of position(a) and speed(b).

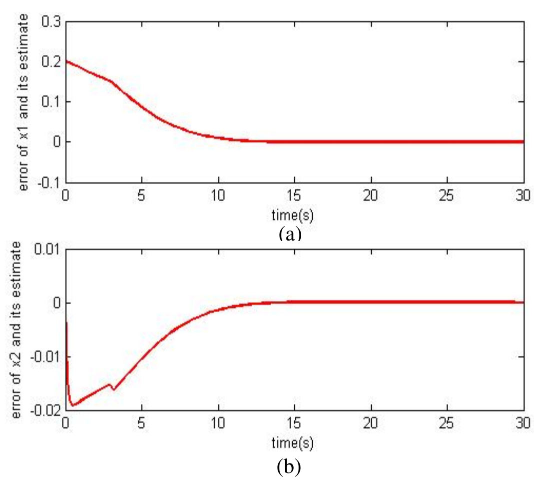

Fig.13 The performance error of the position(a) and the speed(b).

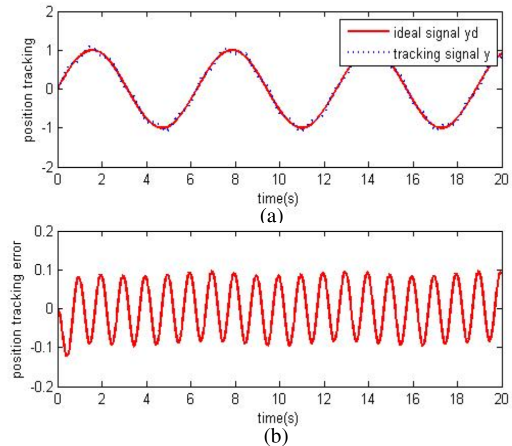

Fig.14 The performance of the controller without the observer. (a)is the tracking performance, (b) is the error performance.

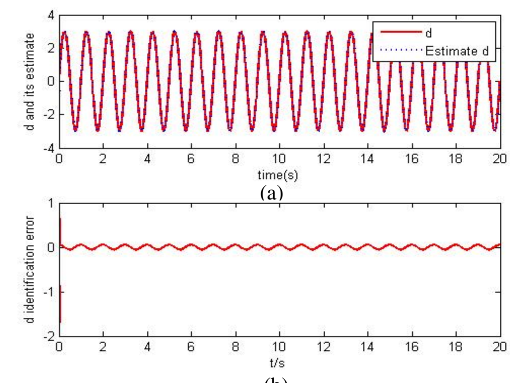

Fig.15 The performance of the controller with the observer. (a)is the tracking performance, (b) is the error performance.

V. The Conclusions

This paper proposed a hybrid control system which combines the Adaptive Fuzzy PID controller and Observer-based 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 surgery. And the simulation results indicates that the time-delay problem and the interference of low-frequency noise has been removed perfectly. However, there are still some shortcomings of this study: not to operate the real performance of the algorithm for the surgical system; The effect of the clamping friction in the structure hasn't been taken into consideration, which is attributed into the environmental interference, so it has to be said that the algorithm still need some improvements. Hence, our future work will concentrate on the developing establishment of the remote MIS system and advancement of the algorithm to carry the product out for actual minimally invasive surgery.

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