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A Novel Application of Positioning Method with Force Feedback for Interventional Surgery Robot

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Abstract – **The interventional surgery is a type of minimally invasive operation which can reduce hospitalization time and greatly decrease patient morbidity compared to traditional methods. In our previous study, a master-slave interventional operation system has been developed. The master side was a Phantom device and the PID control was used through upper machine. To further improve the precision and synchronization performance, two laser range finders were applied to measure the position of the master side in this paper. And positioning compensation on the basis of force feedback was added to the position close-loop. Compared to the previous result, the new method had advantages on precision and accuracy.**

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

I. INTRODUCTION

Endovascular intervention techniques have greatly improved over the last few decades [1]-[3]. There are more and more VIR (Vascular Intervention Robot) have been proposed in previous researches [4]-[5]. In the past the traditional surgery spent patients a lot of operation time and has long recovery time, the burden on patients is heavy. Now intracavity intervention is expected to become increasingly popular in the medical practice, both for diagnosis and for surgery. A lot of diagnosis and medical surgery with an endoscope or a catheter are performed for minimally invasive surgery recently. Much more skills and experience are required for doctors to insert the catheter. In the operation, for example the catheter is inserted through patients' blood vessel. Any mistakes would hurt patients and cause damages.

Two main challenges of such surgery are presented as follows. Firstly, surgeons must be very well trained and possess the skills and experience to insert catheters. Intravascular neurosurgery is much more difficult than traditional surgery and there are few skilled Surgeons who can perform this type of operation. To keep pace with the growing number of patients, a mechanism is required to allow the training of sufficient numbers of surgeons. Secondly, during the operation, surgeons check the position of the catheter tip using the X-ray camera. Although they wear protective suits, it is very difficult to shield the doctor's hands and face from the effects of the X-ray radiation, which may result in radiation-related illness after long periods of exposure.

Many robot-assisted systems are available, and we review a few prominent ones here. The Haifa Rambam Medical Center and the Technion has designed a remote navigation system applied to heart interventions, whose device navigator uses two pairs of rollers to control the axial motion and discrete positioning [6]. And the RNS (Remote Navigation System) successfully crossed lesions with the guide wire in 17 patients. Nan Xiao el al. presented a novel catheter system with monitor and micro force sensors, which can improve operability [7]. This system adopts two wheels tightened by a spring to drive the catheter inserting into the blood vessel. Liu Da el al. has presented a high-precision vascular interventional surgical robot propulsive mechanism designed a propulsive mechanism and carried out several experiments to test the accuracy of propulsive mechanism push or pull catheter [8]. And the experimental results verified the reasonableness and the accuracy of the propulsive mechanism. But they also used the friction wheels to drive the catheter, which is one of main factors that affect the accuracy of the propulsive mechanism. Yogesh Thakur et al. [9] developed a kind of remote catheter navigation system. This system allowed the user to operate a catheter manipulator with a real catheter. So surgeon's operative skills could be applied in this case. The disadvantage of this system is lack of mechanical feedback. T. Fukuda et al [10]. Honghua Zhao et al. had introduced a novel vascular interventional robot including 5-DOF active supporting manipulator and 2-DOF catheter operating system, which can run smoothly and position the catheter operating system accurately [11].

However, there are still rooms for the improvement of accuracy of mechanism. The accuracy of robot catheter system plays an important role in the interventional surgery [12]-[16]. In the previous work, the slave side was controlled through an upper machine so the precision is limited [17]. Moreover, force feedback has an impact on the precision in processing of experiment, which is not considered at previous work. Therefore, a new measurement and control method that satisfies the accuracy demand is expected to be proposed.

In this paper, a laser range finder is applied to measure the axis position of master side, and an optical-electricity encoder is used to measure the rotational position of the master side. The position information was sent to PMAC card to control the slave side. The compensation position was calculated according the force feedback from a Phantom. The surgeons

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operate a connected rod as guide wire at the master side, and the position information will be transmitted to the slave side controller to realize the synchronous movement between the two sides. Due to the stringent requirements for the safety of interventional surgery, position tracking error between master and slave must be minimized during the operation. Aiming at this problem, this paper provides a system with PID control to decrease the tracking error.

II. System Description

The interventional surgery robot was designed with the structure of master and slave. The surgeon console of the system is the master side, and the control part of the guide wire is the slave system. In this intervention operation system, the physicians do the surgery from the master side by using a phantom and a laser range finder, and the slave system is a self-designed multi-axis linkage structure, which is controlled by PMAC motion control card. The movable parts of master side and slave side keep the same displacement, speed and rotation angle. Therefore, the surgeon could operate the system smoothly and easily. At the master side, Phantom offer force feedback and communicates with the computer by Ethernet. The laser range finder and the optical-electricity encoder were connected to the AD converter on PMAC motion control card. At the slave side, the guide wire manipulator communicates with the computer through PCI bus protocol. The overall system diagram is as shown in the Fig.1.

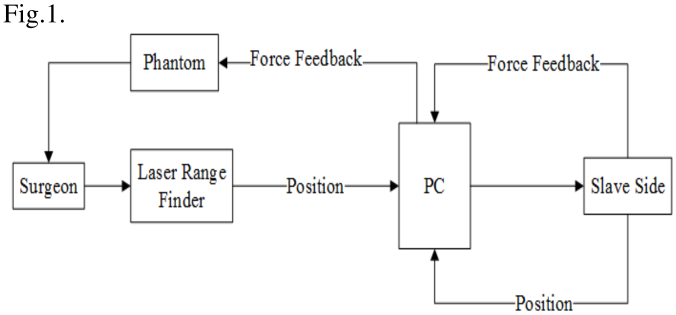
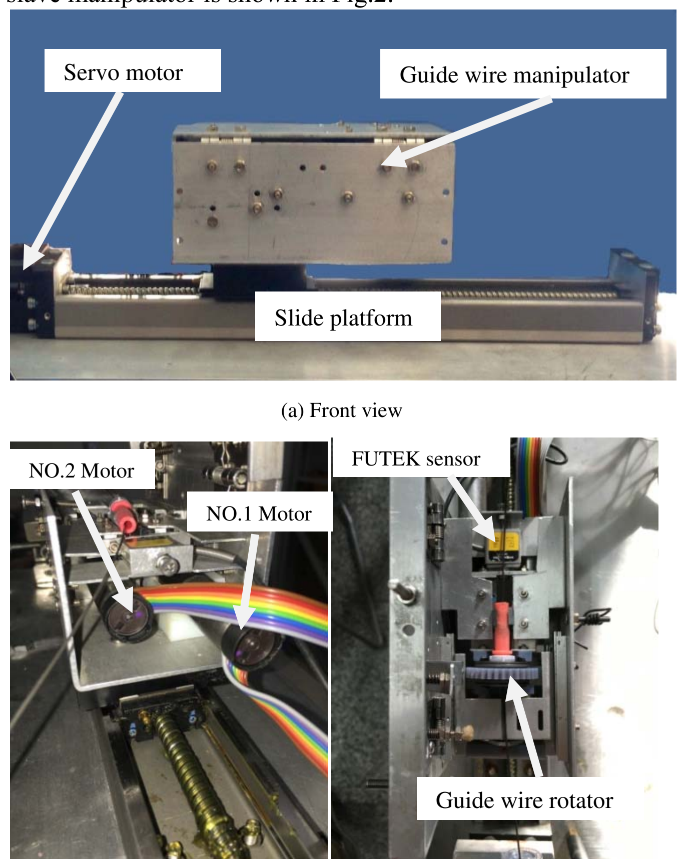


Fig.1 The Master-Slave system sketch map

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. Servo motor on linear sliding platform ensures the axial movement of the guide wire manipulator. The coordinated motion of two EC brushless dc motors could ensure the rotation and the clamping or relax of the guide wire. To ensure the synchronization performance and the accuracy of the movement between master side and slave side, the system adopts the way of 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 realizes the insertion and rotation of the guide wire and the force feedback. The guide wire moves forward and backward in general situation. Moreover, when the guide wire moves to the branch of blood vessel or complicated places, the guide wire's rotation is needed. This part is placed in the operating room, and surgeons manipulate the master side remotely. The motion of the surgical catheter follows the surgeon's operation on master side. The design of slave manipulator is shown in Fig.2.



(a) Front view

(b) Back view (c) Top view

Fig.2 The improved slave system

As is shown in the Fig.2 (a), with the guide wire rotator inside, the guide wire manipulator is on the slide platform. At the left of the slide platform, a servo motor is used to drive the slide platform to move forward and backward, the position of slide platform is determined by the position of the piston rod on master side. The guide wire manipulator includes two brushless dc motors, the guide wire manipulator and a FUTEK mechanical sensor. The two brushless dc motors could determine separation or combination between the guide wire and the guide wire manipulator. The NO.1 dc motor is used to screw or unscrew the gear of the guide wire rotator, and the NO.2 dc motor is used to clamp or relax the tip of the guide wire rotator. When the guide wire rotator is clamped by the NO.2 dc motor and screwed by the NO.1 motor, after the rotator is relaxed, the guide wire could be combined with the guide wire manipulator so that it could rotate following the guide wire rotator and move back and forth following the guide wire manipulator. On the contrary, when the guide wire rotator is clamped by the NO.2 dc motor and unscrewed by the NO.1 motor, the guide wire is separated from the guide wire rotator so that the guide wire manipulator could move back or forth to do the further insertion or extraction. The FUTEK mechanical sensor can measure the force which is transferred from the guide wire, and the Phantom could generate the same force at the master side.

B. The master system

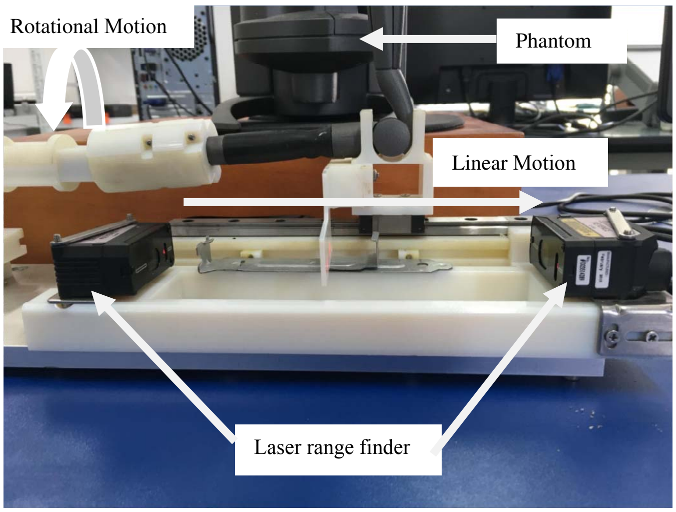


Fig.3 The master part of the robot system

The master part is a phantom and a self-designed laser ranging device (shown in Fig.3). The catheter is inserted by using this mechanism. The laser range finders are used to measure linear motion, which could be more precise and stable than phantom. The phantom device is only used to generate force feedback according the force sensor from the slave side.

This part contains two DOFs, one is axial movement alone the frame, and the other one is rotational movement. On the one hand, axial movement could be measured by the laser range finders and rotational motion could be measured by the optical-electricity encoder. The laser range finders and the optical-electricity encoder are connected to the AD converter of PMAC motion control card. The position information was gathered in real time with a high frequency of 9kHz. Through PLC function of PMAC, synchronization performance between master side and slave side could be guarantied. Both the measurement of axial movement and rotational movement could proceed at the same time On the other hand, the phantom generates the same force transfered from the FUTEK mechanical sensor at the slave side.

III. CONTROL METHOD OF THE SYSTEM

No matter what the design of such system is, safety and accuracy should be ensured. The system control must make the connected rod of master side do the same movement as the guide wire manipulator does. In the previous work, we used PID control without force feedback compensation to realize the consistent following between master side and slave side through upper machine. The maximum error is 4.503mm. The result is shown in Fig 4 and Fig 5.

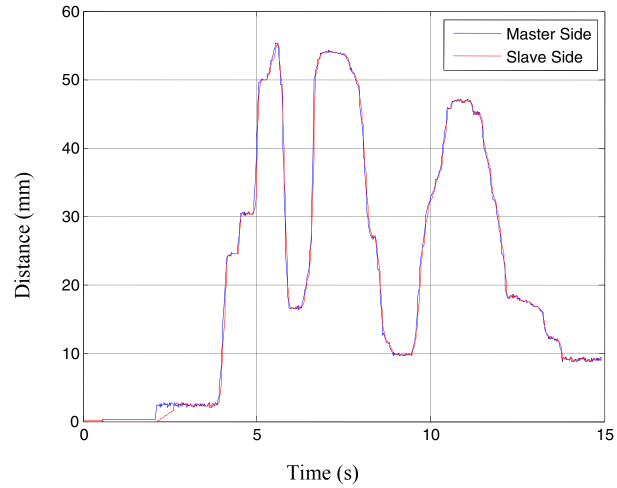


Fig.4 Result of previous work using traditional PID control through upper machine

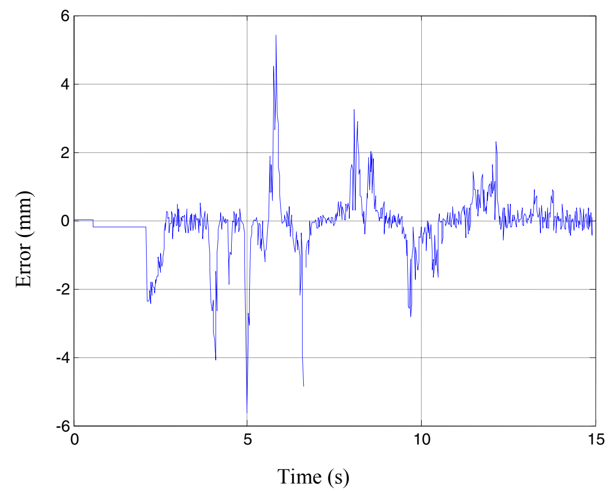


Fig.5 Tracking error of master-slave system in previous work

In this paper, this system was controlled by digital signal processors (DSPs) of a PMAC motion control card which is connected to a computer. The computer sends the basic commands to run or stop the PMAC card. The PMAC motion card will run the PLC program, which is stored in the internal register of PMAC card, to control the motion of guide wire manipulator. The Phantom device in master side could generate the same force as the one measured by FUTEK sensor in the guide wire manipulator. Based on the force feedback information, we add the position compensation to the close loop. Considering the need of the fluent and quick change between the fast motion with low precision and slow motion with high precision, the strategies are different to control under these two conditions. Therefore, we choose fuzzy PID control. The control strategy is shown as following:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} - k_f f(t) \qquad (1)$$

u(t) is the control signal and e(t) is the control error. The control signal thus includes four terms: the P-term(which is proportional to the error), the I-term (which is proportional to the integral of the error), the D-term(which is proportional to the derivative of the error), and the F-term(which is the force feedback compensation). The controller parameters are proportional gain k_p, integral gain k_i, derivative gain k_d, force feedback coefficient. The integral, proportional and derivative part can also be interpreted as control actions. The control block diagram is shown in Fig.6

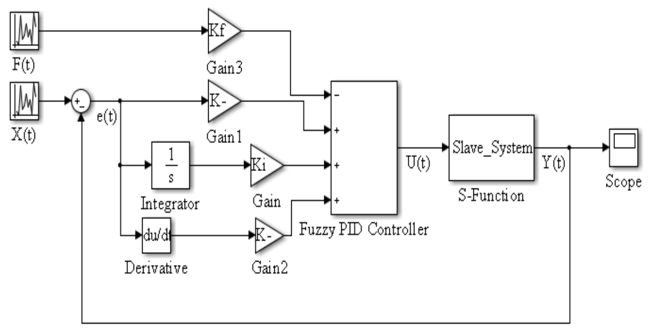


Fig. 6 The fuzzy PID controller based on force feedback

IV. Experiment Results

To evaluate the dynamic performance of the master-slave system, we move the connected rod of the master side from a fixed start point to the end point. In this paper, we do the experiments with an EVE vessel model. It is the model of human blood vessels. The EVE vessel model is shown in Fig.7. The relational graph of the experimental devices is shown in Fig.8.

Fig.7 The model of human blood vessel

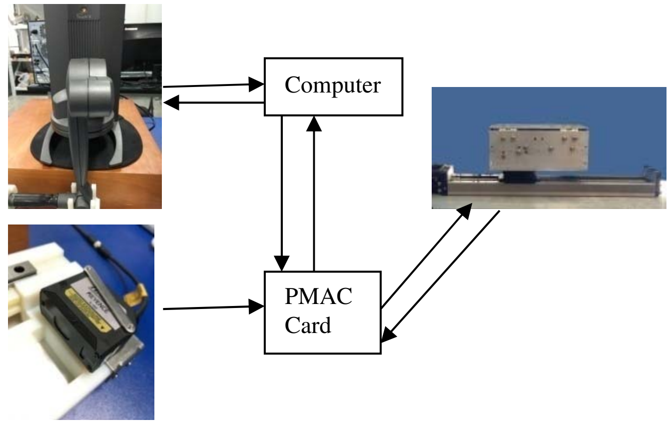


Fig. 8 The relational graph of the experimental devices

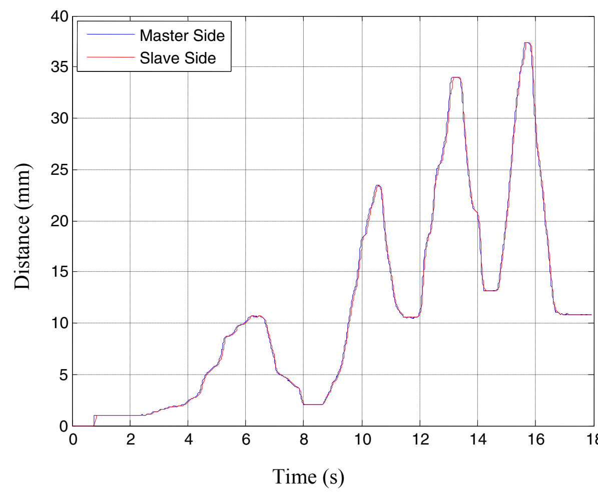


Fig.9 Position tracking of the master-slave system

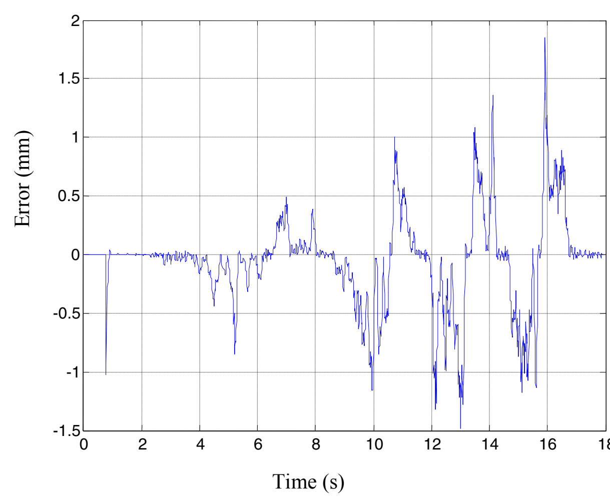


Fig.10 Tracking error of the master-slave system

Figure 9 and Figure 10 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. Dynamic tracking performance of the system error is between -1.5 mm to 2 mm, and the speed of motion is suitable. The slave system is a fuzzy PID control system with appropriate parameters. When there is a variable force feedback, the controller will choose the appropriate strategy and decrease the error appropriately.

From the Fig.9 and Fig.10 we could know that Compared with the previous experiment, the dynamic tracking performance of this system is better than the previous one by using the strategy in this paper.

V. Conclusions

In this paper, a novel positioning method for interventional surgery robot was proposed. We use the laser range finder as the positioning tool for master side, and PLC inside the PMAC motion card is used to control the slave side instead of upper machine program. It achieved better real-time performance and accuracy than before. Besides, we adopted the fuzzy control method and it has better real-time performance and accuracy than the traditional method. 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 an experimental operating device for the current remote catheter interventional surgery doctor, which has great value of training.

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