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A Fuzzy PID Control Algorithm for The Interventional Surgical Robot with Guide Wire Feedback Force

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***Abstract* - During cardiovascular and cerebrovascular interventional surgical procedure, the accuracy of guide wire advance is particularly important for the success rate and safety of surgery, a single PID controller can't adapt to the complex surgical situations, the performance of the system has much room for improvement. In this paper, a fuzzy PID control algorithm with guide wire feedback force was proposed. According to the various situations in surgical procedures, multiple PID controller were designed correspondingly. In the actual surgical procedure, according to the different feedback-force of guide wire, the controller switches between different sets of PID controllers in real time to achieve more excellent performance respectively under different circumstances. Experimental results show that the fuzzy PID controller with guide wire feedback force achieves more excellent performance than the classical PID controller. And the dynamic performance of master-slave control system is better, the following error is reduced, overshoot decreases, and surgical safety greatly increased.**

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

I. INTRODUCTION

Minimally invasive interventional medical engineering or minimally invasive medical technology is a new technology developed rapidly in recent years, it opened up a new aera of medical technology [1]-[4]. Minimally invasive of medical engineering is through the adoption of a series of intervention equipment and materials (or called minimally invasive devices and materials) and modern digital medical equipment for the diagnosis and treatment of operation. Compared with the traditional surgery, interventional treatment, need not operation, with less bleeding, small trauma, fewer complications, and the advantages of safety, postoperative fast recovery, greatly reduce the patients of pain and sufferings, decrease the difficulty of the operation [5]. Operation time and hospitalization time was significantly shortened, costs also decreased obviously [6].

It is considered to be the most valuable clinical medical technology, but because of the complicated operation, high skills needed, operation time is long, X-ray radiation injury problems, they restrict the further development of vascular interventional surgery. Now, the combination of robotics and vascular interventional technology not only can effectively solve the problem, but can be effectively combined with the advantages of professional experience and robotics.

In traditional vascular interventional surgery, with the help of flat DSA image position and force feedback, the doctor can push the guide wire to safety target location, but because of the imaging resolution limit of image equipment and 2 D imaging, the doctor in the process of operation will be more dependent on spinning force feedback, the doctor according to the feedback force subtle changes to adjust their own operations [7]-[9]. In a master-slave robot system, the slave side and the surgeon will be lack of the guidance of the force feedback, this not only affected the surgeon's hand-eye coordination, but also greatly reduce the precision of the guide wire propulsion. At the same time, it increases the operating time and risk. The guidance of the feedback force directly affects the efficiency and success rate of a surgery. Therefore, in the control algorithm of vascular interventional surgery robot system must bring in the feedback force factors [10].

II. INTERVENTIONAL SURGERY ROBOT SYSTEM

The Interventional surgery robot system consists of two parts, the master side and the 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 surgeon does the surgery by controlling a phantom omni, which is the main part of the master side, and the slave system is a self-designed multi-axis linkage structure, holding and pushing the guide wire during the surgery, the slave side is controlled by SMC motion control card, and PMAC motion control card using closed loop control. The movement process of slave part is similar to the manipulation that doctors do the interventional surgery, which 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 receive the controlling message from 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 [11]. In the motion controlling card, classic PID control algorithm was used, to control the linear motion motor and rotate motion motor respectively .The Overall system diagram is as shown in the Fig.1.

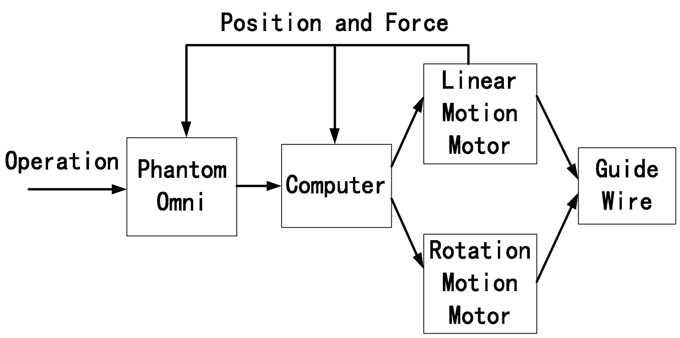

Fig.1 The system sketch map

A. The master side

Master side consist of a Phantom omni, a linear slide, an optical distance sensors and force sensor. Phantom omni has six degrees of freedom as shown by Fig.2, the structure 3d printed to reduce it to 2 degrees of freedom, the linear movement and the rotation movement [12]-[14]. When doctor push the handle of the master side, phantom and a built-in optical distance sensor sensor capable of detecting the distance advance by doctor accurately, then pass the information to the slave side. At the same time, the master side built-in force sensor can detect the pressure between the surgeon's hand and the handle of master side, in order to implement closed-loop control of the master side force feedback.

The structures of the master side are shown in Fig.2:

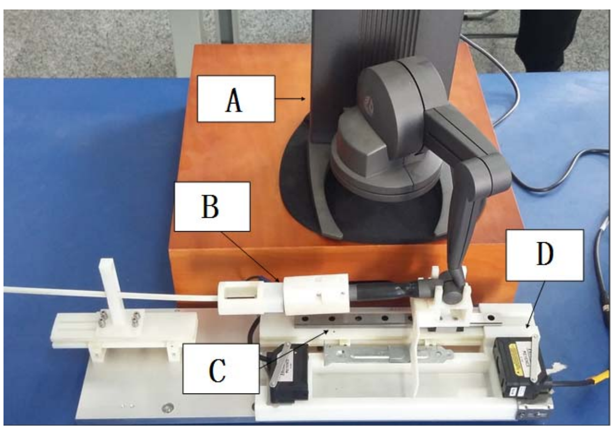

Fig.2 Structures of the master side

Where part A is Phantom Omni, part B is pressure Sensor, part C is Linear Slide, and part D is Optical Distance Sensors.

B. The slave side

Slave side consist of a linear slide unit, three motor, guide wire holding structure and sensors, a motor convert rotary motion to linear motion to control the propulsion of the guide wire by a screw structure, another motor control guide wire rotary motion, two motor has its own encoder respectively, so to be able to accurately record their respective angular displacement, to calculate the advance distance and Angle of rotation of guide wire. The third motor control guide wire relaxation and clamping, the slave side to accomplish the continuous progress and continuous rotation of guide wire, by the reciprocating movement and orderly relaxation and clamping.

Pressure sensors can detect the guide wire resistance in the operation process, and can feedback the resistance to the master side and the controller in real time. Also impose the guide wire resistance to the master side, let the doctor perceiving the movement of the guide wire accurately, facilitate its correct operation, and help the operation completed.

The resistance that force sensor detected in real-time, can also be used for the fuzzy PID control algorithm with thread feedback force proposed in this paper. The guide wire resistance detected in the process of operation, can be used as the conditions of the real time switching between many set of PID controller.

The structures of slave side are shown in Fig. 3 and Fig.4:

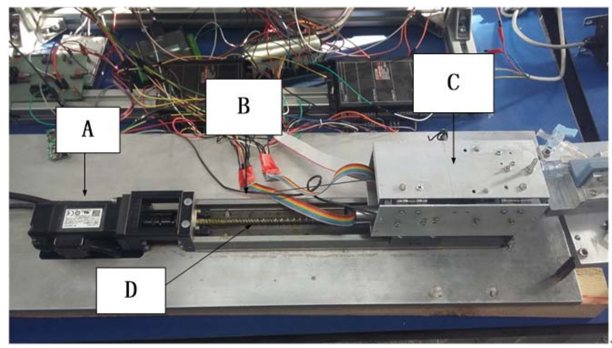

Fig.3 Structures of slave side (outside)

Where part A is the motor controls the linear movement, part B is the linear slide, part C is the guide wire holder, and part D is the screw structure.

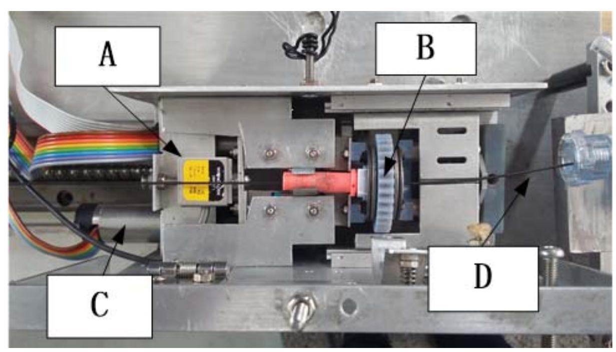

Fig.4 Structures of slave side (inside)

Where part A is the force sensor, part B is the guide wire holder, part C is the motor controls the rotation movement, and part D is the guide wire.

III. THE CONTROLLING METHOD OF THE SYSTEM

A. Classic PID control algorithm

With the increasingly development of science and technology, the requirement of precision ,response speed and system stability of automatic control system become more and more high, due to its simple structure and strong robustness, classic PID control algorithm is widely used in various occasions [15].

The basic principle of PID control is put error into proportional, integral, differential three processes, send a linear combination of the three results as an input of the controlled object [16].

The diagram of the PID controller are shown in Fig.5:

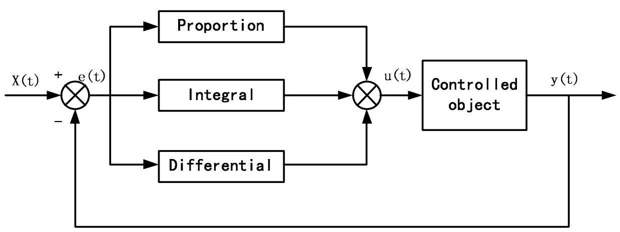

Fig.5 The diagram of classic PID controller

Different objects can be controlled by adjusting the three parameters of PID control algorithm to obtain satisfactory results, PID control is a linear controller, the equation of PID control is:

$$e(t) = x(t) - y(t) \tag{1}$$

The control law for PID controller is:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{2}$$

Where k_p is proportion gain coefficient, k_i is integration time coefficient, k_d is differential time coefficient [17].

B. Fuzzy PID control with force feedback

Although there are robustness and stability of classic PID control algorithm, but during surgery, different position of guide wire, leading doctors have different operating strategies, fixed coefficient PID control algorithm can not be applied to all cases, there is much room for improvement of the control performance [18].

Here we propose a fuzzy PID control algorithms with a guide wire feedback force. For different guide wire movement strategy, different sets of PID controller was designed with the changes of guide wire force feedback [19]-[22]. When in surgery, the guide wire advance strategy switched in real time among multiple sets of PID controllers, different PID controllers are used for different situations, in order to achieve better dynamic performance and static performance than traditional PID controller.

We divided the feed-back force into 3 fields, small medium and big. For each field, there is a set of PID parameter. During the experiment, the controller switches between these 3 set of PID controller softly.

The equation of these fuzzy controller is as follow:

$$u_1(t) = k_{p1} e(t) + k_{i1} \int_0^t e(t)dt + k_{d1} \frac{de(t)}{dt} \tag{3}$$

$$u_2(t) = k_{p2} e(t) + k_{i2} \int_0^t e(t)dt + k_{d2} \frac{de(t)}{dt} \tag{4}$$

$$u_3(t) = k_{p3} e(t) + k_{i3} \int_0^t e(t)dt + k_{d3} \frac{de(t)}{dt} \tag{5}$$

$$u(t) = k_1 \times u_1(t) + k_2 \times u_2(t) + k_3 \times u_3(t) \tag{6}$$

If $0 \leq |f| < F_{t1}$:

$$k_1 = |f| / (F_{t1} - 0), k_2 = 1 - |f| / (F_{t1} - 0), k_3 = 0; \tag{7}$$

If $F_{t1} \leq |f| < F_{t2}$:

$$k_1 = 0, k_2 = |f| / (F_{t2} - F_{t1}), k_3 = 1 - |f| / (F_{t2} - F_{t1}); \tag{8}$$

If $|f| > F_{t2}$:

$$k_1 = 0, k_2 = 0, k_3 = 1; \tag{9}$$

Where u is the control input of the controlled objected, k_{pj}, k_{ij}, k_{dj} (j=1,2,3) is the coefficients of 3 PID controller in the fuzzy algorithm respectively, f is the feedback force of guide wire, F_{t1}, F_{t2} are the threshold value of feedback force which controllers switches according to, k_1, k_2, k_3 are the weight coefficients of the 3 controller in the whole algorithm, which makes these 3 controller switches softly.

For example, when the guide wire advance to straight and thick blood vessels, since the guide wire advance has less resistance in this situation, the speed that doctor push the guide wire will be higher than any other case, thus should increase the proportion gain coefficient of the PID controller to attain the dynamic performance when the guide wire reach a given objectives positions.

When the guide wire advancing encountered obstacles, the guide wire feedback force increases, then the guide wire should advance slowly. Consider the safety of operation, in this circumstance the overshoot control system allows decreases, to prevent cardiovascular from damages. Therefore, at this time the integral coefficient should be smaller [23]-[26].

IV. Experimental Results and Analysis

A. Experiment for classic PID control algorithm

In the traditional PID algorithm experiment, the master side back to the initial position, after system start, push the handle manually, reciprocating movement multiple times, then linear motion motor rotation, then guide wire advance and retreat with the operators in real-time.

And Fig.6 is the picture of vessel model we use in the experiment.

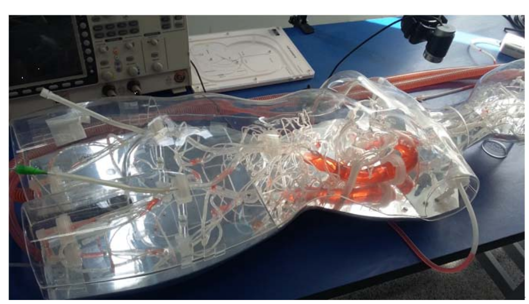

Fig.6 Vessel model

For each experiment, the result consist of :

1) The position of master side and guide wire;

2) The absolute error of guide wire's movement;

3) The feedback force of guide wire force sensor detected.

The result of classic PID control algorithm are shown in the Fig.7-Fig.9.

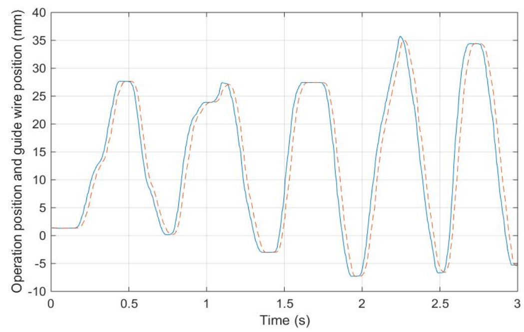

Fig.7 Compare of input and output of classic PID controller

Fig.7 is the comparison of input and output, in this picture, full line represent the movement of master side, dotted line is the movement of guide wire, as we can see from the picture, the dynamic performance of the classic PID controller isn't good.

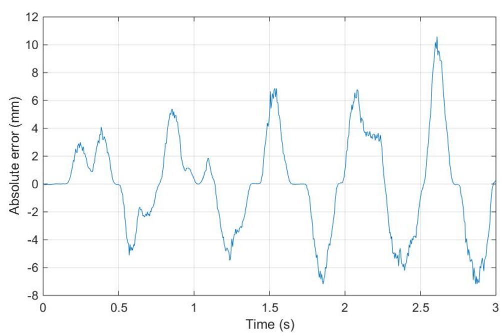

Fig.8 Absolute error of classic PID controller

Fig.8 is the absolute error of output compare with the desired output, as we can see from Fig.8, the peak of error reaches 10mm.

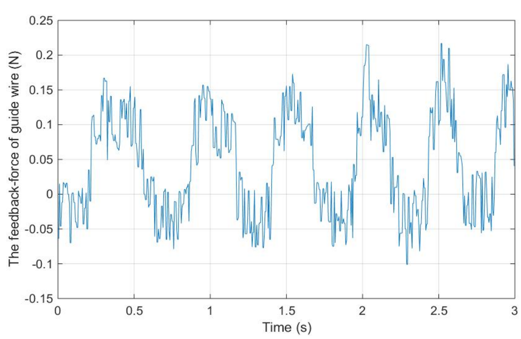

Fig.9 Feedback-force of guide wire

Fig.9 is the feedback f of guide wire force detected during the experiment. As we can see, the feedback force fluctuated between -0.15N and 0.2N.

B. Experiment for Fuzzy PID control algorithm with force feedback

In the Fuzzy PID controller experiment, we divided the feed-back force into 3 fields, small medium and big. For each field, there is a set of PID parameter. During the experiment, the controller switches between these 3 set of PID controller softly.

The results of fuzzy PID controller with feedback force are shown in Fig.10-Fig.12.

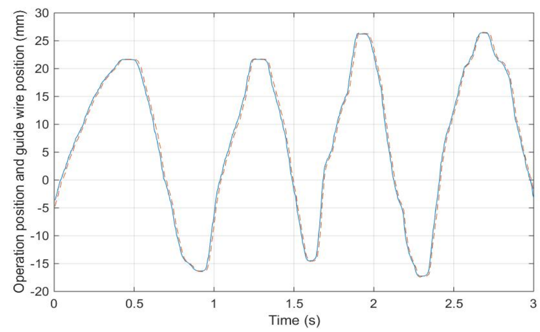

Fig.10 Compare of input and output of classic PID controller

Fig.10 is the comparison of input and output, as we can see from the picture, the dynamic performance of the fuzzy PID controller is much improved than the classic PID controller.

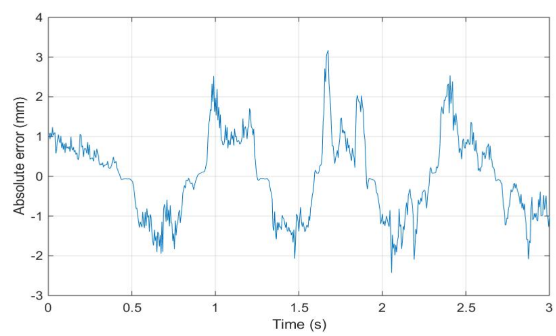

Fig.11 Absolute error of fuzzy PID controller

Fig.11 is the absolute error of output compare with the desired output, as we can see from Fig.11, the peak of error is below 3.5mm, also much improved than classic PID controller.

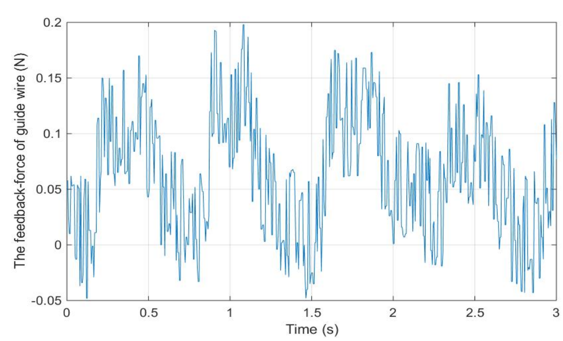

Fig.12 Feedback-force of guide wire

Fig.9 is the feedback f of guide wire force detected during the experiment. As we can see, the feedback force fluctuated between -0.15N and 0.2N, similar to the classic PID experiment.

As we can see in the experiment result, the results of the fuzzy PID controller with guide wire feedback force are better than the classic PID controller, the absolute error is smaller, and the dynamic performance are improved. The result shows that this fuzzy control algorithm can perform better and safer than classic PID controller during robotic Interventional Surgery.

V. Conclusion and Future Work

This paper proposed a fuzzy PID control algorithm with guide wire feedback force. The controller's control strategy changes due to the guide wire feedback force changes. It decrease the following error of the Interventional surgery robot system. However there is still some flaws in this study: due to the manual operation, operation in each experiments were not the same, it may led to the inaccuracy in the experiment results; during the feedback force detection, there are some data point missing occasionally.

The future work of this study is to analyze the pattern in the guide wire feedback force, and design the controller for each pattern, to achieve the better control performance.

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