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Cable-driven Interventional Operation Robot with Stribeck Friction Feedforward Compensation

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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 previous work, the interventional operation robot was developed to send catheter or guidewire. The master side was a Phantom device and the PID control was used through upper machine. To further improve the precision and synchronization performance, a cable-driven slave side of interventional operation robot was developed. Friction model was built and friction feedforward algorithm was added to closed-loop control of the robot in this paper. Compared to the traditional motion control algorithm, the new method had advantages on dynamic performance.**

Index Terms - Minimally invasive interventional surgery, Master-slave system, Cable-driven, Sribeck friction feedforward

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 driven mechanism of slave side was by lead screw [17]. Moreover, the friction between manipulator and platform of slave side was left out of consideration, which causes the insufficient of dynamic property. Therefore, a new measurement and control method that satisfies the accuracy demand is expected to be proposed.

In this paper, a cable-driven mechanism was designed to replace the lead screw driven mechanism. Firstly, the Stribeck friction model was built according LuGre friction model. Secondly, to verify the model, the command information was sent out by upper machine, and the position information will be transmitted to the slave side controller to realize the synchronous movement between the two sides. The controller provides closed-loop control, and two comparison experiments were done to verify that the friction model promoted control performance of the robot.

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 device, and the slave system includes slide platform and guide wire manipulator, 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 could detect position information of user’s hand. 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.

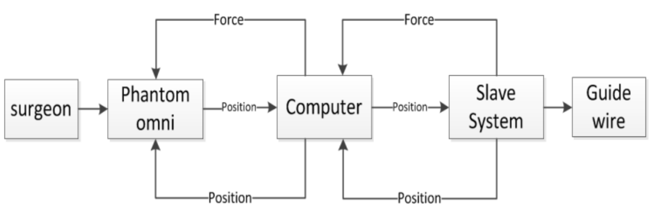
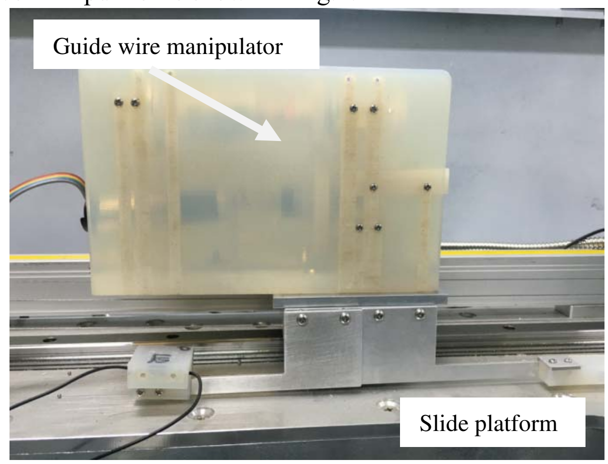


Fig.1 The Master-Slave system sketch map

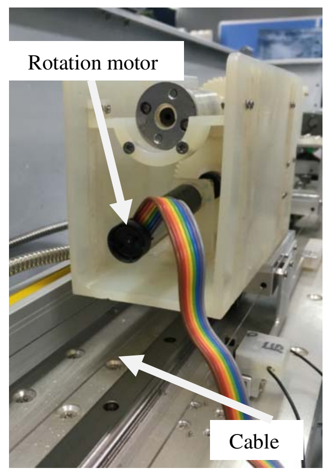
In the master-slave system, both the linear sliding table servo motor and the brushless dc motor of the slave system have their own encoder. Therefore, both the distance of the linear motion and rotation angle can be calculated accurately through the encoder in order to achieve the desired control results. Servo motor on linear sliding platform ensures the axial movement of the guide wire manipulator. The coordinated motion of EC brushless dc motor and electromagnetic clutch could ensure the rotation and the clamping or relaxing 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 with friction feedforward. This control mode guarantees the high control performance of the robot.

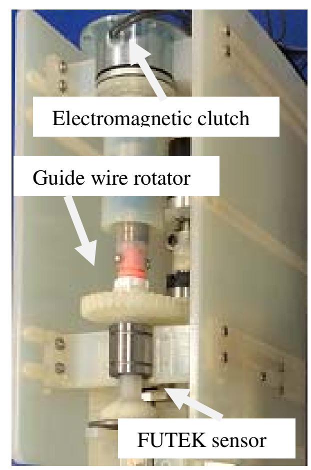
A. The slave system

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 Guide wire manipulator

As is shown in the Fig.2 (a), with the guide wire rotator inside, the guide wire manipulator is on the slide platform. Under 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 a brushless dc motors, the guide wire rotator, a FUTEK mechanical sensor and an electromagnetic clutch. The brushless dc motors and electromagnetic clutch could determine separation or combination between the guide wire and the guide wire rotator. The dc motor is used to screw or unscrew the gear of the guide wire rotator, and the electromagnetic clutch is used to clamp or relax the tip of the guide wire rotator. When the guide wire rotator is clamped by the electromagnetic clutch and screwed by the dc 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 electromagnetic clutch and unscrewed by the dc 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

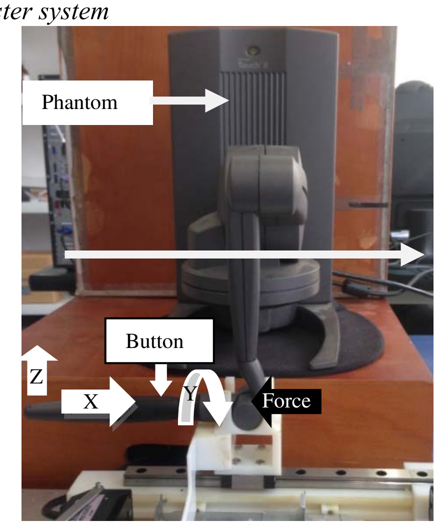


Fig.3 The master part of the robot system

As the 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. As to 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.

III. Control Method of The System

LuGre friction model was common a research result by Sweden rand institute of engineering technology and France Grenoble laboratory. This model was put forward on basis of Dahl model. LuGre model considered rigid body surface was contacted by elastic mane, the stiffness of lower surface is greater than the stiffness of upper surface. When force is applied, because of the tangential force, mane deformation occurs. The force created by the deformation is namely friction force. When the tangential force reaches a certain critical point, mane generates sliding displacement. At the steady state, the mane of deformation is determined by the system operation speed. The lower the speed is, the smaller the deformation is; the higher the speed is, the bigger the deformation is, as is shown in Fig.4.

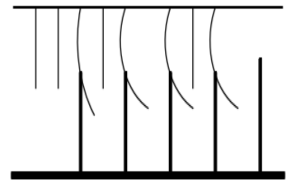


Fig.4 LuGre friction model [29]

LuGre model mathematical expressions are shown as follows:

$$f = \sigma_0 z + \sigma_1 \frac{d_z}{d_t} + \sigma_2 v \quad (1)$$

$$\frac{d_z}{d_t} = v - \frac{\sigma_0}{s(v)} z\,|v| \quad (2)$$

$$s(v) = f_c + (f_s - f_c) e^{-(v/v_s)^2} \quad (3)$$

Variable z is average deformation of mane; σ_0 is mane stiffness; σ_1 is microscopic damping coefficient; σ_2 is viscous friction coefficient; $s(v)$ describes the Stribeck effect; v_s is Stribeck speed; f_s is static friction force.

When the system is in steady state (dz/dt=0), the corresponding relationship of friction and speed as follows:

$$f(v) = [f_c + (f_s - f_c) e^{-(v/v_s)^2}] + \sigma_2 v \quad (4)$$

To identify the actual friction parameter of the system, plenty of experiments were done to get enough data. In low speed and high speed stage, several parts of data were selected to do curve fitting. The corresponding relationship between velocity and friction force is shown in TABLE.I.

TABLE I
The corresponding relationship between velocity and friction force

Velocity (mm/s)	0.2	0. 4	0.8	1	2
Friction (N)	0.796	0.783	0.768	0.753	0.732
Velocity (mm/s)	5	8	10	15	20
Friction (N)	0.757	0.778	0.803	0.881	0.960

The experimental data was drawn into a scatter diagram, and curve fitting of the data could calculate the static parameters. The curve fitting was shown in Fig.5.

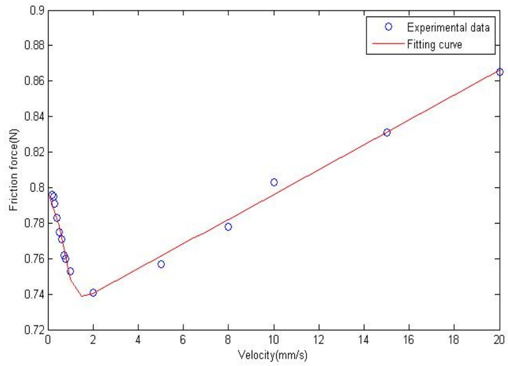


Fig.5 The curve fitting of static parameters

MATLAB provides nonlinear least-square fitting function Isqcurvefit. The function can be called directly in parameter identification. Because scatter diagram of speed and friction has been gained, probable values of parameters can be estimated. The identification result is shown in TABLE.II.

TABLE II
The identification result

Static friction parameter	F_c (N)	F_s (N)	(mm/s)	σ_2 (Nm s/m)
Identification result	0.7263	0.7976	0.8063	0.0070

The algorithm block diagram is shown in Fig.6, the specific compensation control is added to the control loop.

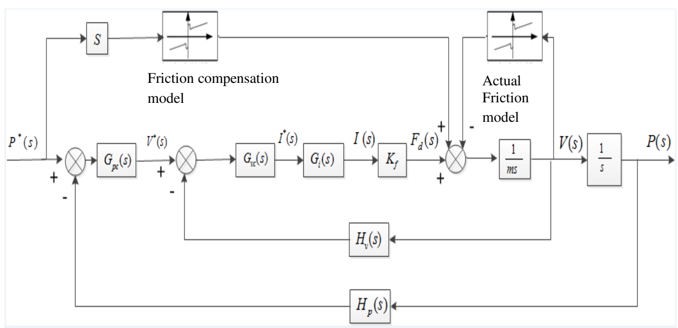


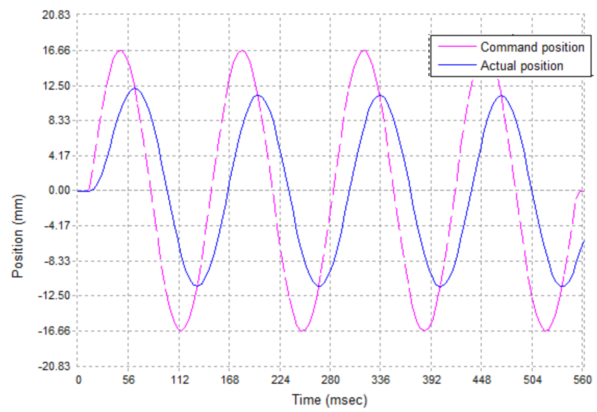
Fig.6 The control algorithm block diagram of the robot system

IV. Experiment Results

To evaluate the dynamic performance of the master-slave system, sinusoidal signal were sent to the motor controller from upper machine. In this paper, we do the experiments with an PMAC control card. The card could compose a control system to complete various types of function with various types of industrial PC, electrical amplifier, motor and sensor. In practice, it can meet the practical needs for a specific function set according to its characteristics of hardware and software. To realize the algorithm mentioned in this paper, we use visual studio software in industry PC to control lower computer.

The PMAC control card is shown in Fig.7. The relational graphs of the experimental results are shown in Fig.8 and Fig.9.

Fig.7 The PMAC control card



Time (s)

Fig.8 Robot servosystem without friction feedward model

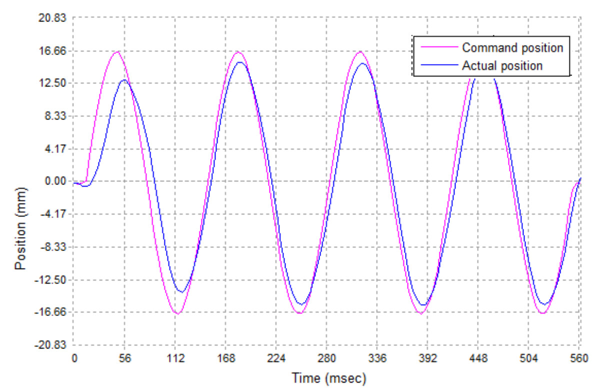


Fig.9 Robot servosystem with friction feedward model

Figure 8 and Figure 9 show the position tracking experimental results. According to these results it can be found that robot servosystem with friction feedward model has a better dynamic tracking performance than the servosystem without friction feedward model. When the robot servosystem was without friction feedward, the frequency of sinusoidal signal was added the to 7.4Hz. The actual peak value was 0.707 time than command peak value, and the maximal following error was 8.33mm. When the robot servosystem added friction feedward, the maximal following decreased obviously.

From the Fig.8 and Fig.9, we could know that compared with the robot servosystem without friction feedward, the dynamic tracking performance of this system is better by using friction feedward compensation in this paper.

V. Conclusions

In this paper, a cable driven interventional operational robot was developed. We use phantom device as positioning tool at master side, and use a self-designed guidewire or catheter manipulator to control the guidewire or catheter. In the motion of manipulator, the Stribeck model was built according actual friction force between the guidewire or catheter manipulator and the motion platform. With the friction compensation, the system achieved better real-time performance than the system without the friction compensation. Due to Stribeck friction model mainly compensated the steady state error, at the frist period of the following motion it still takes some difficulty for slave side to follow the command motion. However, this master-slave system has reached the demanded dynamic performance for the current remote catheter interventional surgery doctor, which has great value of training.

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