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A Novel Design of Grasper for the Interventional Surgical Robot

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***Abstract* - In the interventional surgery, the catheter guide wire advancing and position accuracy is very important for the success rate and safety of the operation. In our newly developed vascular intervention surgery robot system, the slide unit of catheter and guide wire which provide the movement has a very big improvement space. In this paper, we proposed a gripper for holding a guide wire of a catheter. When slide reaches the movement limit and need to move backward, it will hold the guide wire to prevent it from retreating and affect the safety and accuracy of the experiment. The performance evaluation experiments of the novel grasper were done. The experimental results show that the grasping clamp effectively clamps the catheter to improve the accuracy of the operation and can meet the design requirements.**

Index Terms –Grasper; Interventional Surgical Robot; Master-slave system; Performance evaluation

I. INTRODUCTION

Nowadays, diseases like vascular infarction, brain tumor and other kind of heart diseases remains to be a big cause of sudden illness in the world. Minimally invasive surgery through the interventional radiology is being considered as a way of these diseases' treatment and has attracted more and more attention. In the 1960s, Charles Dotter intervened in interventional radiology for the first time through advances in medical imaging and catheterization [1]. The invention of angiography at 1920s was a huge step which allowed doctors to visualize the vascular and diagnose diseases like vascular infarction. The catheter is first used in the interventional procedure for the use of inflatable balloon in the angioplasty to dilate the stenosis. The subsequent development of the catheter structure and material allows it to position the weakened blood vessels and deploy an intravascular stent to enhance vascular strength. Interventional Surgery Treatment of intravascular disease has been a common alternative to open surgery since the 1990s, and patients are treated with faster recovery rates and lower mortality compared to clinical outcomes of open surgery. Apart from the use of surgical techniques in vascular surgery, it also developed in nerve intervention technology to treat the central nervous system aneurysm, vascular malformations and other diseases [2].

Minimally invasive surgery is widely used in surgery over the past decade, because it can reduce pain of patients and allow for quick recovery. However, the minimally invasive surgery causes several difficult problems for surgeons: the partial protection for the radiation, heavy radiation protection garments, chronic neck, and back pain, due to the specific surgical procedure and small work space [3]. Therefore, development of the surgical support devices with the application of robot technology is in demand [4]. Researchers have become increasingly interested in intravascular interventional robotic catheter insertion systems which use remote control. These system has the advantage including the ability to reduce radiation exposure [6], doctors can remotely manipulate the robot to perform surgery without radiation, and increase accuracy and stability of the surgical procedure, reduce the contact of the vessel wall and eliminate tremor, even increase the operator's comfort by enabling the doctor to sit and perform the surgery [7]. The application of force sensors and force feedback compensates for some of the tactile hints that the operator needs during remote operation of the catheter navigation, resulting in a significant increase in the safety and reliability of the surgical robotic system [8]. Although such robotic navigation systems have been widely studied, most of the existing commercial grade-level surgical systems have overlooked the operating habits that the operator has formed during the operation of the operating table. Thus, the recent design of the master-slave intravascular interventional surgical system is moving towards more ergonomic aspects in order to take advantage of the operator's experience-related skills [9]. This paper will introduce the master-slave surgical robot we use and a novel grasper which is used to improve the accuracy of surgery.

II. INTERVENTIONAL SURGICAL ROBOT SYSTEM

This interventional surgical system is composed of two parts, the master side and the slave side. The surgeon do the surgery by using phantom geomagic touch haptic device in the master side, which is the operator’s control part. By pushing and dragging the touch bar handle, the movement of haptic devices will be transferred to the slave side through PC and PMAC motion control card, creates the same circumstance as the surgeon is holding the catheter or the guide wire at the same time. For the motion control, a typical PID control algorithm is used to control the linear motion motor and the rotary motion motor [10]-[17]. The slave side has slide pushing device to control and holding the catheter or guide wire. The connection system structure is shown in Fig.1.

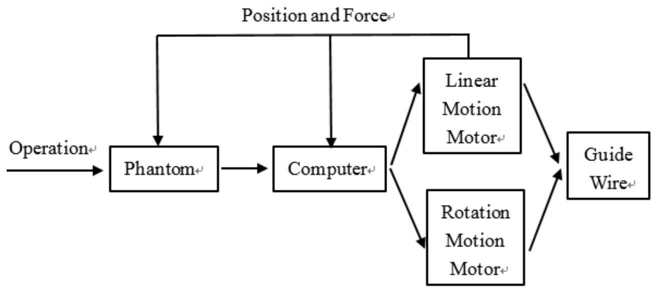


Fig.1 The system sketch map.

A. The master side

The master side has a haptic device and a PC. The haptic device has six degrees of freedom but only back/forward linear movement and rotation movement is used during the operation. When the operator move or rotate the touch bar handle, the sensor in the haptic device will be able to detect the movement amount or the rotation angle, and control the slave side do the same movement. The haptic device can control the catheter and the guide wire, and it make the operator get a vivid operating experience [14]. The structures of the master side are shown in Fig.2.

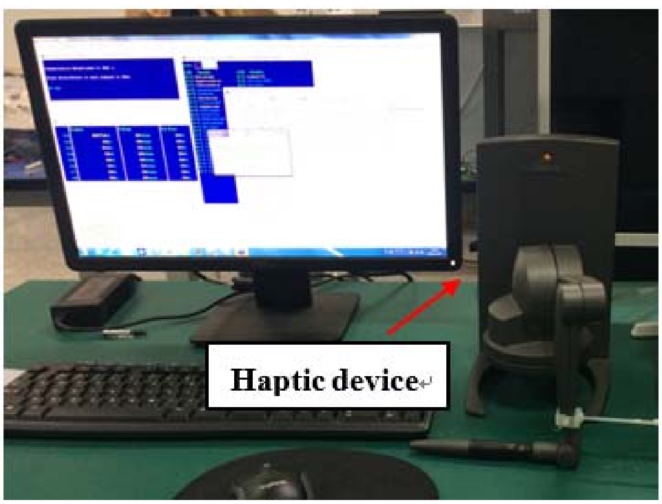


Fig.2 Structure of the master side.

B. The slave side

The slave side is consist of a mobile platform, a shell, a gripping unit, and a driving unit. One 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 mobile platform was designed to manipulate the shell, which mount a driving unit and a gripping unit shown in Fig.3. When the surgeons operate (pull or push) the master side, the mobile platform move forward or backward by executing the command of control signal imparted by the master side. Meanwhile, the gripping unit and the driving unit, as well as the guide wire, will have the same movement with the mobile platform, because they are mounted on the shell. The slave side operates the guide wire in reciprocating promotion instead of continuous promotion, which can imitate the surgeon operation absolutely, and take good advantage of the surgeon's existing dexterity. The force sensor can measure the proximal resistance when the catheter and guide wire is pushing forward, and feedback the resistance to the PC in the master side, make the operator know the position of guide wire and catheter precisely. Force sensor real-time detection of resistance can be used for fuzzy feedback control algorithm with thread feedback force. The wire resistance detected during operation can be used as a real-time switching condition between many groups of PID controllers.

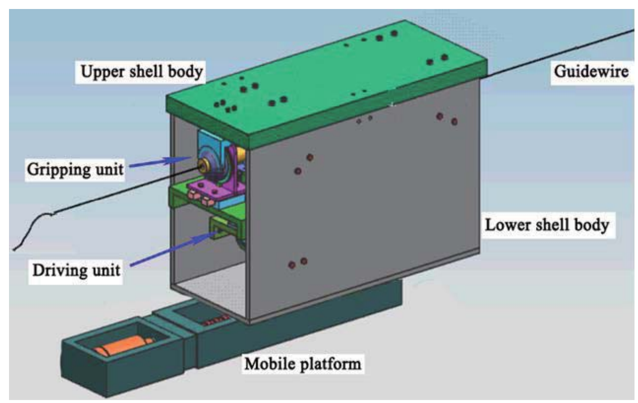
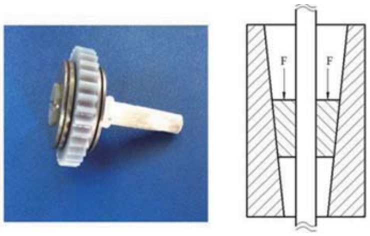


Fig.3 Structure diagram of the slave side.

III. SYSTEM IMPROVEMENT

After the whole system was carried out, we did the system performance evaluation experiment. In the evaluation experiment, we used a human vascular structure model which called EVE (General Aniography Type C, FAIN-Biomedical, Inc. JP) (Fig.4**)** as a human body's replacement.

Fig.4 EVE model.

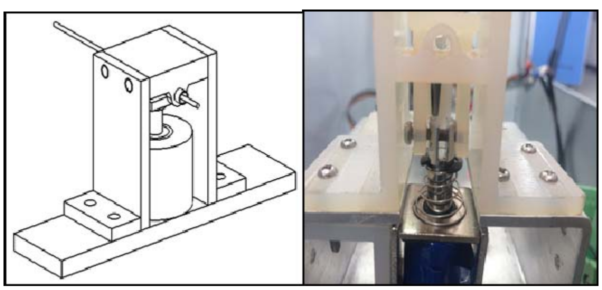


(a) (b)

Fig.5 The guide wire gripper: (a) Structure diagram of guide wire gripper, (b) Schematic diagram of the cone clamping theory on the guide wire gripper.

As the system can handle the main surgery requirement, there are still shortcomings need to improve. In the experiment, the slide unit needs to go backwards when it reached the maximum of its stroke. The unit has its fixture, using a cone clamping theory to clamp and loosen the guide wire and the catheter (Fig.5 (a)). When the right end of the jig is fixed and the left end is pushed inward by the rotation of the gear, the pawl gap guide wire holder becomes small, so that the guide wire is held by the holder (Fig.5 (b)). Also, the guide wire can be pushed out by the reverse of the gear to push the left end of the guide wire [16].

When the slide unit is going backward, neither the catheter nor the guide wire should move with it. However, according to the previous experiment results, the catheter will be dragged when the unit is moving backward even the gripper is loose. Consider of the surgery's accuracy requirements and the patient's safety, the catheter and guide wire must stay fixed. Under this circumstances, a clamping device is needed. As is shown in Fig.6, a novel grasper has been proposed. The grasper's structural concept is like a bionic shell, it will stay loose during the surgery, and when the slide unit needs to go backward, the cover will go down and clamp the catheter or the guide wire which is like the grasper2 shown in Fig.7 [17].



(a) (b)

Fig.6 The grasper's structure diagram: (a) Schematic diagram of the grasper, (b) The picture of the real object.

The power source of this structural is an electromagnet, the electromagnet is connected with the grasper by helix pair. The grasper is placed at the end of the slave side platform to ensure the catheter can be control. The grasper use friction to clamp the catheter, as we know that the formula of friction is

$$F = \mu * F_N \quad (1)$$

where the dynamic friction factor μ of the catheter is a fixed value, the main variable that affects friction is the positive pressure F_N. On the basis of different catheter type, the positive pressure should be different in case it is too loose to clamp the catheter or to tight that damage it. Due to this gripper unit is placed on the platform, the slide unit backward speed should coordinate with it, in case the unit move back to fast made the catheter or the guide wire fractured.

With the assistance and cooperation of the moving platform, slider units, motors and other components, the catheter and guide wire can easily switch between different modes of movement and the slave side can simply move forward/backward and rotate.

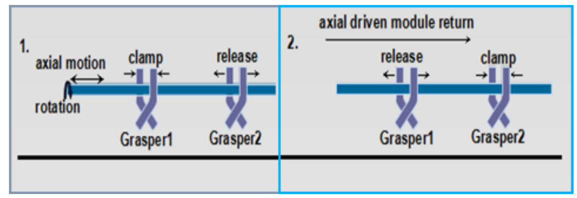


Fig.7 The clamping method of graspers [17].

IV. Evaluation Experiment

The electromagnet has a rated clamping force of 20N, but if the catheter is clamped with this rated clamping force, the catheter wall may be damaged and may be bent at the time during the propulsion, cause failure of the experiment. According to the previous research, the clamping force is less than 2.5N, so we did the experiment based on this conclusion.

A. The calibration experiment of the film pressure sensor

In the experiment, we measured the clamping force with the film pressure sensor which shown in Fig.10 (a). The film pressure sensor's resistance decreases with the increase of pressure, it was pre-calibrated when purchase. The pre-calibrated result was shown in Table.1, by using MATLAB we got the equation of the fitting curve which shown in Fig.8.

TABLE I
PRE-CALIBRATED RESULT OF THE FILM PRESSURE SENSOR

Pressure/N	Resistance/KΩ	Voltage/V
0	0	5.0
0.2	340	4.8571
0.4	175	4.7297
0.6	98	4.5370
0.8	52.2	4.1961
1.0	34.1	3.8662
1.2	23.2	3.4939
1.4	21.48	3.4117
1.6	18.67	3.2560
1.8	17.69	3.1943
2.0	16.82	3.1357

According to this fitting curve, the relationship between the pressure force and voltage of the film pressure sensor can be shown as

$$U = -727.4F^5 + 3381.9F^4 - 479.40F^3 + 1817.1F^2 - 809.7F^2 + 4994.1 \quad (2)$$

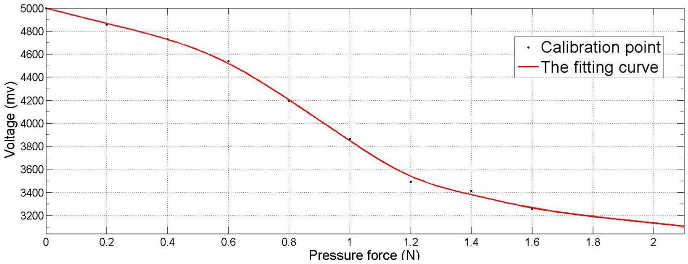


Fig.8 Calibration results and curve fitting results.

where U is voltage of the film pressure sensor, F is the pressure force. The equation is used to acquire the clamping force according to the voltage measured of the film pressure sensor. Due to the range of film pressure sensor itself, the voltage of film pressure sensor changes distortion a little when the pressure is bigger than 2N.

B. Performance evaluation experiment of the grasper

In the experiment, the clamping force is changed through the spring. The spring can be placed either on the top or the bottom of the electromagnet, changing the compression length or the stiffness by using different spring can make different clamping force. The detail of the experiment is shown in the Fig.9.

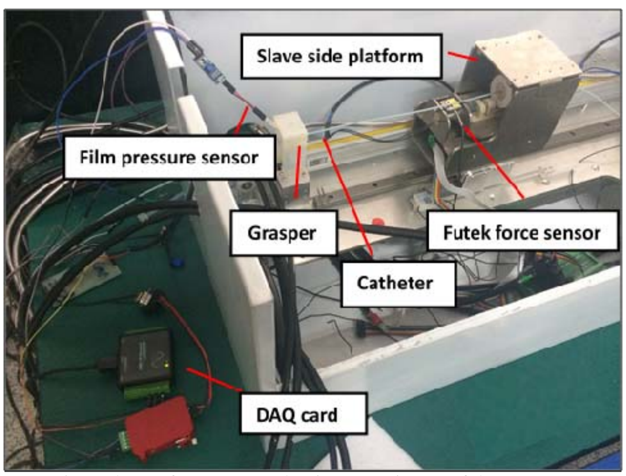
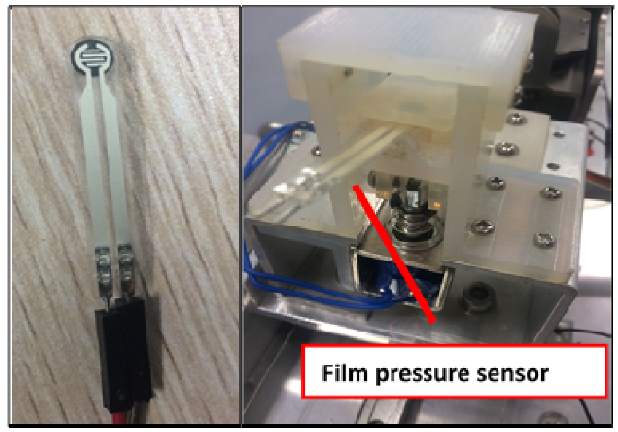


Fig.9 The performance evaluation experiment of the grasper.

The experiment's purposes was to measure the friction force between the catheter and the grasper in different clamping force, so the film pressure sensor (IMS-00004-C20, Suzhou Chang Xian Optoelectronics Technology Co., Ltd, CN) was placed between the cover and the catheter. As is shown in Fig.10 (b), the film pressure sensor measured the clamping force of the grasper and ensured the structure of the grasper is not damaged. The friction force between the catheter and the grasper was measured by the futek force sensor (LSB200-FSH00103, Futek Advanced Sensor Technology, Inc. JP) which assembled on the slave side platform. When the slave side platform clamped the catheter, the push and pull resistance force of the catheter will transmitted to the futek force sensor via the force transmission unit.

The performance evaluation experiment aims to find out the relationship between the clamping force and the friction force to evaluate the performance of the grasper, which plays a key role in improving accuracy of insertion of the catheter. In the experiment, both the grasper and the slave side platform were clamped the catheter. When the slave side moved forward, the friction between the grasper and the catheter was first to be static friction, and it increased rapidly to be maximum static friction force and became dynamic friction. The maximum friction force was detected by the futek force sensor when the slave side began moving. According to the data acquired, a curve of the relationship between the clamping force and the friction force was obtained, and the fitting curve was also acquired through doing curve fitting by MATLAB.



(a) (b)

Fig.10 The clamping force sensing device: (a) Structure diagram of the film pressure sensor, (b) The installation of the film pressure sensor.

As is shown in Fig.11, the blue curve is the linear interplant curve, and the red one is the fitting curve. The relationship between the clamping force and maximum static friction force can be shown as

$$f_F = 0.2766 f_C^3 - 2.1561 f_C^2 + 5.1159 f_C - 0.0702 \qquad (3)$$

where f_F is the maximum static friction force between the catheter and the grasper, f_C is the clamping force, which is acquired by the film pressure sensor which placed between the cover and the catheter. Through changing the spring's compression length, we got different maximum static friction force for different clamping force of electromagnetic clutch. Due to the character of the film pressure sensor, the clamping force can't be detected any more when bigger than 2N. When the clamping force reaches to 2N, the friction force nears to 3.5N which can meet requirement of the friction for clamping the catheter.

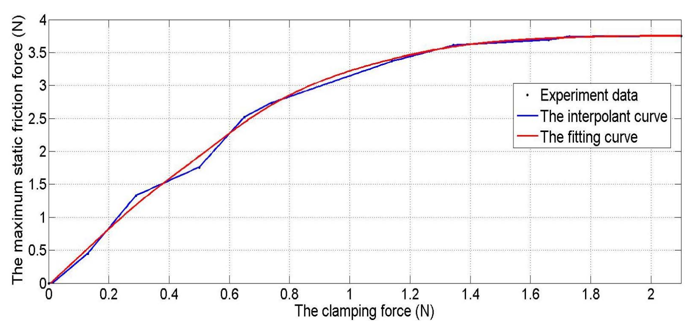


Fig.11 The relationship between clamping force and maximum static friction force.

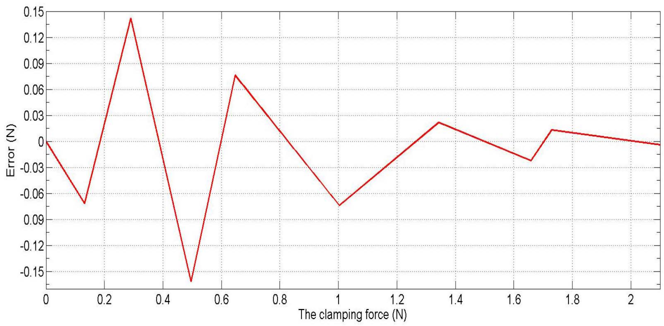


Fig.12 The error between measured value and fitting value of friction force.

As is shown in Fig.12, the error between measured value and fitting value of friction force. The error curve can be used to improve the performance of the grasper with error compensation. When the clamping force is less than 0.6N, the friction force is unstable and too little to meet the requirement of the friction for pushing the catheter. Then the range of the clamping force between 0.6N and 2N is our best choice.

The maximum clamping force of the grasper is also needed to obtain to guarantee not to damage the catheter. We did an experiment of clamp and relax the catheter 10 times in 5 seconds, the experiment didn't cause irreversible indentation to the catheter. And according to the maximum pressure mark on the package of the catheter, its maximum pressure is 1100 psi [18]-[21], which is much bigger than the grasper can cause. So the grasper can satisfy the demand that clamping catheter without relative displacement and damaging catheter.

V. Conclusion and Future Work

In order to ensure the surgery's accuracy requirements and the patient's safety, a novel grasper has been proposed for the interventional surgical robot to keep the catheter and guide wire stay fixed, if the slide unit needs to go backwards when it reached the maximum of its stroke. It can be used to improve insertion accuracy of the catheter. And the performance evaluation experiment of the grasper for the system has been done. The experimental results indicate that the developed novel grasper for the robotic catheter system is effective. The maximum clamping force of the grasper cannot damage the catheter, which can satisfy the design demand. In future work, we will try to change the power unit of the grasper from electromagnet to steering gear, which make the clamp force more controllable and can be adjust flexibly during the surgery.

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