Proceeding of the IEEE
International Conference on Information and Automation
Hailar, China, July 2014

Performance Evaluation of the Novel Grasper for a Robotic Catheter Navigation System

Shuxiang Guo[*1,*2], Jian Guo[*1], Lin Shao[*1]
*1 Tianjin Key Laboratory for Control Theory & Application in Complicated Systems and Biomedical Robot Laboratory
Tianjin University of Technology
Binshui Xidao 391, Tianjin, China
guoshuxiang@hotmail.com

Peng Wang[*1] and Yunliang Wang[*1]
*2 Intelligent Mechanical Systems Engineering Department
Faculty of Engineering
Kagawa University
Takamatsu, Kagawa, Japan
shaolinsdkd@163.com

***Abstract* – This paper proposed a novel grasper for a novel master-slave robotic catheter navigation system in Vascular Interventional Surgery (VIS). The developed novel grasper can imitate the catheter grasping motion of the surgeon during VIS. The grasper is a key factor to drive the catheter into the vessel accurately. It adopts a common structure like the pliers, which can guarantee that the catheter can be clamped on the same axes with other via hole. The clamping force can be adjusted by the screw through changing the entered length of the screw to change the compression length of the spring. The clamping system consists of two graspers both master side and slave side respectively. The graspers clamp the catheter just like the surgeon's hand and the clamping method of the grasper imitates the surgeon's operation. The performance evaluation experiments of the novel grasper were done. The experimental results indicated that the grasper was effective to clamp catheter tightly to increase accuracy of surgery, which can satisfy the design demand.**

Index Terms - Vascular interventional surgery, Catheter, Grasper, Performance evaluation.

I. Introduction

Vascular Interventional Surgery (VIS) becomes an increasingly important role in Minimally Invasive Surgery (MIS) which becomes increasingly popular in the medical practice with the development of medical technology [1]-[3]. There are more and more VIR (Vascular Intervention Robot) have been proposed in previous researches [4]-[5]. And the researchers are growing more interested in robotic catheter operation systems for vascular interventional surgery. 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. 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 [9]. In their system, the catheter is clipped and moved forward with two trolleys. These above mentioned systems can all realize the clamping action to drive the catheter inserting into the blood vessel through using the friction wheels, but the slippage between catheter and the friction wheel is the disadvantage unable to avoid. Yuan Wang et al. have proposed a novel catheter clamping force measure method, and it is suit for their developed catheter navigation system, in which the measurement structure uses two pieces of hard rubbers to clamp the catheter [10] [11]. The method can achieve a high accuracy when the translation speed is smaller than 50 mm/s. But the grasper in their system may lead to the deformation of the catheter so that it may damage the catheter. The accuracy of robot catheter system plays an important role in the interventional surgery [12] [13]. So a grasper satisfying the accuracy demand is expected to be proposed.

In this paper, we proposed a novel grasper for a novel master-slave robotic catheter system in VIS. The surgeons operate the real catheter at the master side, and the operating information from the master side will be transmitted to the slave controller to realize the synchronous movement in the two sides. There is a clamping unit in each side. The clamping unit in the master and slave side can realize synchronous movement through a remote control signal from the master side. And the novel grasper in the clamping unit adopts a common structure of the pincher, which can imitate the grasping action of the surgeon's hand. The grasper can clamp the catheter firmly when the slave manipulator operates the catheter moving in axial and radial direction. Compared with the previous clampers which clamp catheter relies on the roller friction, the novel grasper can grasp the catheter tightly without relative sliding or damaging the catheter. The design of this system can meet the requirements of ergonomic. The grasper's performance evaluation experiments have been done. The experimental results indicated that the system was reliable. And the grasper can clamp the catheter tightly without slippage or damaging the catheter, which satisfies the design demand.

978-1-4799-4100-1/14/$31.00 ©2014 IEEE

II. The Novel Master-Slave Robotic Catheter System

A. Outline of the master-slave system

The master-slave system is a closed-loop control system which the master side transmits control information to the slave side while the slave side transmits feedback force information to the master side. Fig.1 shows the conceptual diagram of the master-slave robotic catheter system. As shown in the Fig.1, the robot catheter system consists of a master side and a slave side the two parts. The surgeon operates a real catheter while viewing a monitor on the master side. The operating information will be acquired by sensors and transmitted to the slave side. The slave mechanism will drive the motors to insert the catheter into blood vessel when receiving the operating information. Motions of the catheter on the slave side follow the motions of the catheter on the master side. In the meantime, an IP camera is used to monitor the process of the operation and the condition of the operating room. If the catheter contacts the blood vessel wall, the force information will be detected by sensors and transmitted to the surgeon’s eyes. And the driving force of the slave manipulator will be acquired and transmitted to surgeon’s hands as force feedback. As if the surgeon operates a real catheter beside the patient. The safety of the surgery can be improved by this method.

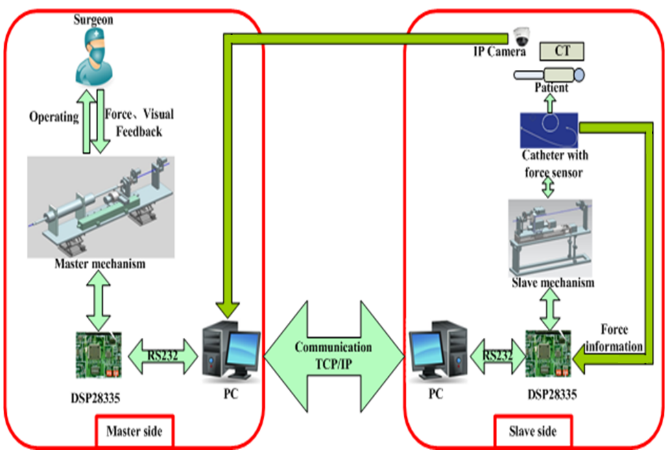

Fig.1 The conceptual diagram of the robotic catheter system

The main task of master side is to acquire the operating information of surgeons and send it to the slave side. The information is processed by a DSP controller and transmitted between the master side and the slave side by the TCP/IP communication protocol. The slave side mainly follows the master side to drive the catheter moving in same method. In the meantime, the slave controller can also acquire the contact force between the catheter tip and blood vessel by tiny sensors and send it to the master side to improve the safety of the vascular interventional surgery. There are two graspers in each side to work alternately to clamp the catheter inserting into the blood vessel. And the two graspers can be controlled to achieve alternate work by a key in the master side. The control signal from the key in the master side can be transmitted to the slave side to realize synchronous movement in the master side and the slave side.

B. The Design of the master manipulator

The master side is the operating platform for the surgeons to operate the interventional surgery. The Fig.2 is the diagram of the designed master manipulator. The doctor can operate a real catheter as the conventional catheter interventional surgery, which is the key character of the master side. There are two main tasks of the master side. The first one is to obtain the motion information of the catheter which is operated by the surgeon. And the motion information includes the axial and radial information two aspects. The other one is to transmit the operating force which is transmitted from the slave manipulator to surgeon’s hands directly. And the operating force contains axial operating force information and rotation torque information. Grasper1 and grasper2 work alternatively to realize the insertion of the catheter. Grasper1 connects to the piston rod with nipple joint, and grasper2 is installed on a board which is fixed on the installation board of the lifting platform. The surgeon operates the catheter move with piston rod when the catheter is grasped by grasper1. The surgeon could adjust the position of the piston rod and other linked structure that can keep the catheter still when the catheter is grasped by grasper2 and the grasper1 loosing. The working height of the master side can be adjusted through the lifting platform according to different operating habit and demand.

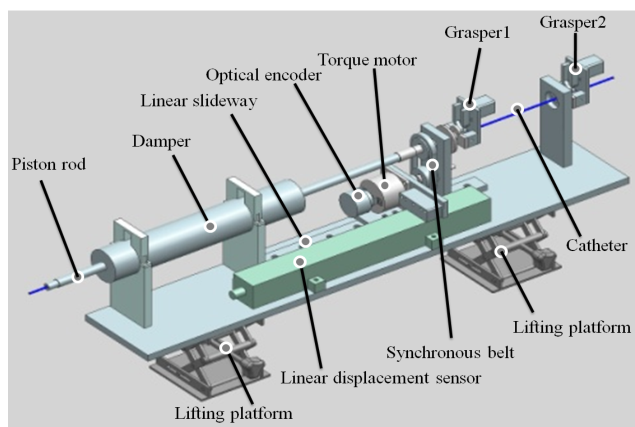

Fig.2 The master manipulator

On the master side, the motion of the catheter operated by surgeon has axial motion and radial motion two degrees of freedom. In order to acquire the axial motion information of the catheter, a linear displacement sensor has been adopted, which uses a floating magnetic block with non-contact as the sliding end. Therefore, the sliding end will be moved without any fraction, which reduces the resistance in the axial motion. The location of the block and also the position of the catheter can be obtained through the output voltage. The linear displacement sensor is installed on the installation board of the lifting platform, and the sliding end is installed on an adapter plate of the linear sideway. The movement between the sliding end and the piston rod of the damper is synchronous. The catheter and piston rod are fixed together through grasper1. Then motion information of the sliding end equals to the axial motion information of the catheter. The radial motion of the catheter is acquired by the optical encoder which is installed on the torque motor. The synchronous belt connects the torque motor and the piston rod. Therefore, the torque motor and the piston rod have the same rotation angle which is detected by the optical encoder. In meanwhile, force feedback plays an important role in improving the safety of the tele-operating robotic system. The feedback force can be transmitted back to the surgeon's hand through the catheter in our design.

Compared with the developed master-slave robotic catheter system in our previous study, which can simulate surgeon's operating skill to insert and rotate catheter, the best advantage of this system is that the surgeon can operate a real catheter. The novel system accords with the requirements of ergonomic and can make full use of natural catheter manipulation skills obtained in conventional catheter navigation.

C. The Design of the slave manipulator

The slave side realizes the insertion and rotation of the catheter and the force feedback. Surgical catheter moves forward and backward in general situation unless the branch of blood vessel or moving difficulty appears which needs the catheter's rotation. The motion of the surgical catheter follows the surgeon's operation on master side. The design of slave manipulator is shown in Fig.3.

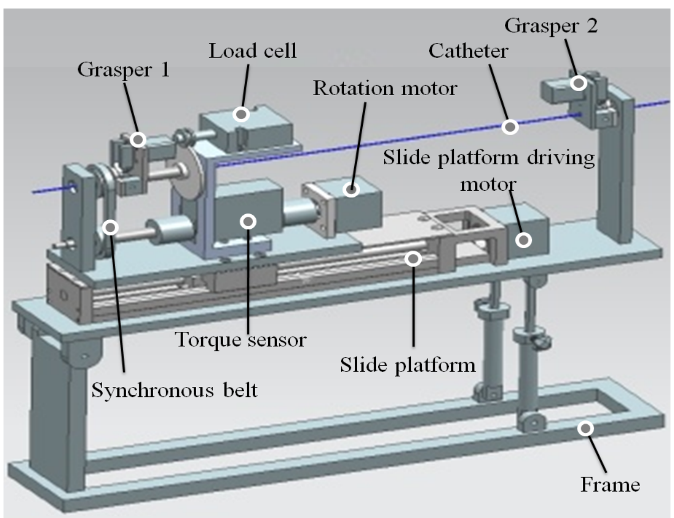

Fig.3 The slave manipulator

The slide platform is fixed on the supporting frame which can be adjusted easily to change the interventional angle from 0° to 45°. A motor is used to drive slide platform to move forward and backward, the position of slide platform is determined by the position of the piston on master side. And the Rotation motor is used to realize the rotation of the catheter. Two graspers have been designed to simulate the surgeon's grasping action. All the graspers on master side and slave side have the same structure. The manipulator can realize the axial and radial motion of the catheter when the catheter is clamped by grasper1. The grasper1 clamps the catheter just as the surgeon's hand, so the axial driving module which is fixed on the sliding end of the linear platform can hold the catheter moving synchronously. The catheter keeps its position and the catheter driven part can move smoothly when the catheter is clamped by grasper2 and released by grasper1. The selected grasper used for clamping the catheter is related to the two graspers on master side. To realize axial movement, all catheter driven parts are placed and fixed on sliding end of the slide platform. The slide platform is driven by a stepping motor through screw. The rotation motor drives the catheter to move in radial direction through the synchronous belt.

The load cell is fixed on the slide platform. A clamp plate is fixed on the load cell, and it is linked to the plate which is stalled on the axle of grasper1. The axle of grasper1 is supported by two bearings, which allows the clamping part to have a micro displacement. The clamp plate can move freely in the axial direction without affecting the rotating motion of the plate. When graper1 clamps the catheter to move on axial direction, the counter-acting force of the catheter applying to graper1 will lead to a micro displacement of the axle of grasper1. And the micro displacement will be transmitted to the clamp plate. Through the plate, the counter-acting force is acquired by the load cell.

Torque sensor is applied to measure the torque information during the rotation operation. The torque sensor is linked to rotation motor and the axle of the pulley below. The rotation movement of the catheter and the torque sensor is synchronous. So the torque sensor can measure the rotation torque of the catheter. And the torque information will be transmitted to the master side and generate a torque feedback to the surgeon's hand.

The detecting of contact force between the catheter tip and blood vessel plays an important role in improving the safety of the vascular interventional surgery. To obtain the contact force information, a novel type of catheter sidewall tactile sensor array was developed in our previous research [14]. And the relationship between the contact area and the conductivity was analyzed using finite element analysis method [15]. The contact information acquired on the slave side will be transmitted to the master side.

III. STRUCTURE AND PERFORMANCE ANALYSIS OF THE DEVELOPED GRASPER

In our robotic catheter system, a novel grasper has been proposed. The clamping unit in the master and slave side adopts the same structure and number of grasper. The clamping unit is composed of two graspers, which clamp the catheter alternately in order to imitate insertion action of the surgeon's hand. The Fig.4 shows the structure of the proposed grasper. In order to guarantee the catheter to be clamped on the same axis with other mounting hole, we adopted a common structure like the pliers. The cam fixed on the stepping motor can change the opening angle of the clamp piece so that it can achieve the action of clamping and releasing the catheter. The structure of the clamp piece is like the pliers so that they can open or close easily. The clamp piece is closed in the original state. The size of the grasper is shown in the Fig.4. It's the first generation of prototype; we will optimize it to become smaller and more portable.

Two clamp pieces can hold the catheter firmly by using the spring to compress. The length of the spring compressed can be adjusted by the entered length of the screw. As is known that the spring's compressive force is proportional to the length, so the clamping force can be changed through adjusting the entered length of the screw. We can always find an appropriate clamping force to clamp the catheter as long as an appropriate spring and an appropriate compressing length of the spring is chose. The clamping end of the clamp piece is covered with sponge, which can increase the friction force between catheter and the grasper. Compared with the previous grasper using roller friction method, the novel can clamp the catheter tightly without relative sliding.

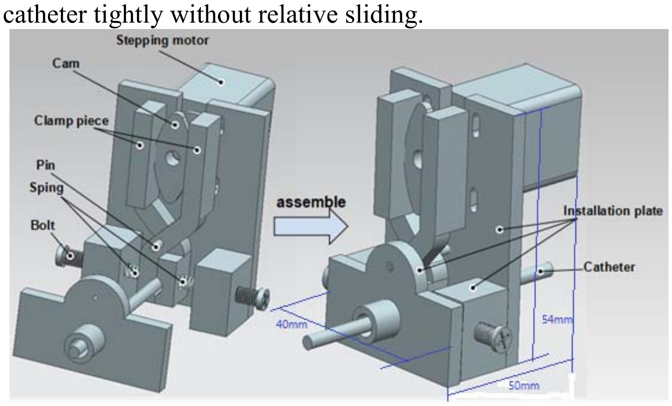

Fig.4 The structure of the grasper

The graspers clamp the catheter just like the surgeon's hand. The clamping method of the grasper is shown in the Fig.5. When the grasper1 clamps the catheter and the grasper2 releases, the catheter is fixed with the axial driven module through the grasper1 so that it has the synchronous axial and radial movement with the driven module. It means that the catheter can drive the driven module in the master side and the driven module can drive the catheter in the slave side. When the grasper2 clamps the catheter and the grasper1 releases, the catheter will keep its position and the driven module will return to start the next operation. Therefore, the catheter will be pushed to the lesion location through the two steps in alternate cycle.

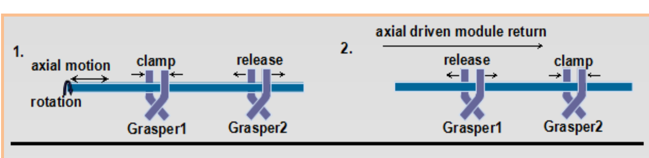

Fig.5 The clamping method of graspers

IV. Performance Evaluation Experiments of the Grasper

In the vascular interventional surgery, the grasper is a key factor to make the surgery success. Therefore, the choice of the clamping force and clamping way is an important factor. It needs to guarantee that the catheter is clamped tightly without damage and driven without relative sliding. In order to protect the catheter from damaging, it is significant to know the safety of the grasper. So we need to do performance evaluation experiments. In our experiment, we have measured the clamping force with the pressure sensitive rubber whose resistance decreases with the increase of pressure. And we have done the calibration experiment of the pressure sensitive rubber firstly.

A. The calibration experiment of pressure sensitive rubber

In order to improve the accuracy of the force measurement, we have done the calibration experiment of the pressure sensitive rubber. Fig.6 shows the details of the experiment. Pressure sensitive rubber is a kind of high polymer, its resistance decreases with the increase of pressure. But when the pressure reaches a certain value, the resistance will almost not be changed. In this experiment, pressure is measured by the load cell which is driven by a micro-displacement to squeeze the pressure sensitive rubber. The parameter measured of the pressure sensitive rubber is its voltage which is measured in the series circuit. We have measured the voltage of the pressure sensitive rubber in the series circuit when pressure is increased by the interval of 0.2N. We have got the data and drawn the graph of the relation between voltage of pressure sensitive rubber and pressure. Fig.7 shows the graph of calibration of pressure sensitive rubber.

The measuring range of load cell is from -5N to 5N, which correspond to the voltage range from -5V to 5V acquired into the PC. The measuring range of load cell has a linear relationship with the output voltage, and we will acquire the output voltage to evaluate the detecting force of the load cell. As shown in the Fig.7, the red curve is the data we measured in fact, and the blue curve is the fitting curve. We can get the equation of the fitting curve through MATLAB. The equation (1) shows the relation between pressure and voltage of the pressure sensitive rubber.

$$\mathrm{U_r} = -217.1F^3 + 1734.7F^2 - 4573.5F + 46529 \qquad (1)$$

where $\mathrm{U_r}$ is voltage of the pressure sensitive rubber, F is the pressure force. The equation is used to acquire the clamping force according to the voltage measured of the pressure sensitive rubber. Due to the nature of pressure sensitive rubber itself, the voltage of pressure sensitive rubber changes a little when the pressure is bigger than 2N.

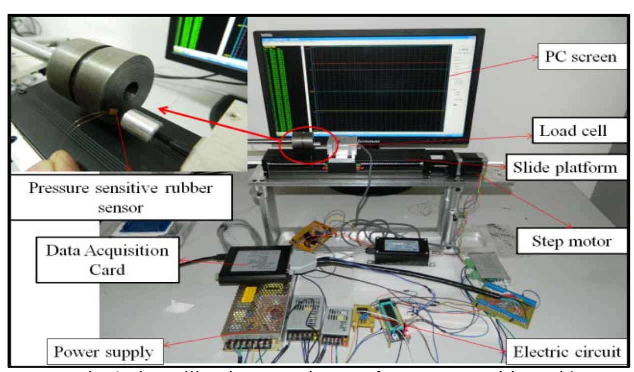

Fig.6 The calibration experiment of pressure sensitive rubber

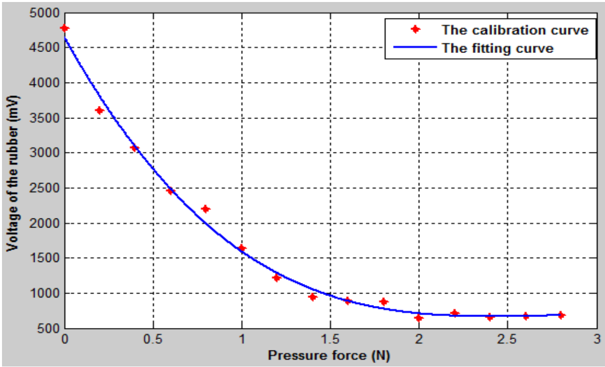

Fig.7 Calibration results and curve fitting results

B. Performance evaluation experiment of the grasper

In the experiment, the clamping force is changed through changing the compression length of the spring. And the compression length of the spring can be adjusted by changing the precession length of the screw. The detail of the experiment is shown in the Fig.8. We measured the friction force between the catheter and the grasper in different clamping force by spring dynamometer pulling the catheter. In order to measure the clamping force and increase the friction between the catheter and the grasper, we pasted the pressure sensitive rubber in coverage of sponge on the clamp piece using double faced adhesive tape. The installation of the pressure sensitive rubber is shown in the Fig.9.

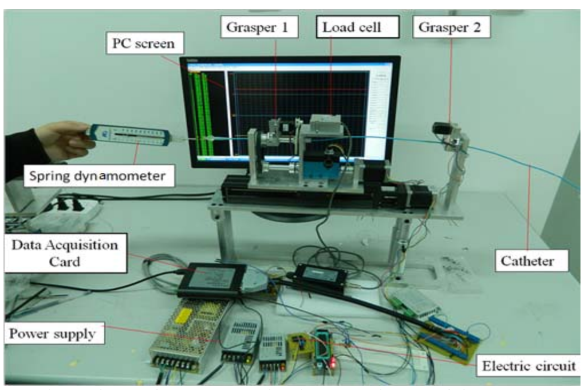

Fig.8 The performance evaluation experiment of the grasper

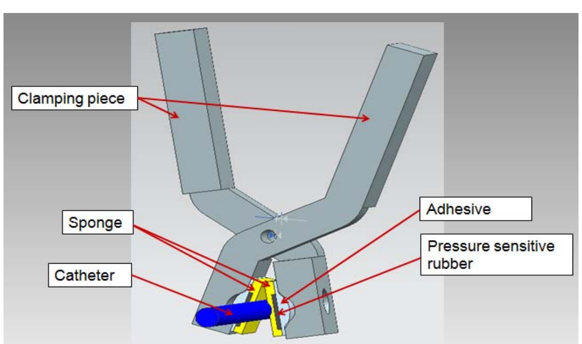

Fig.9 The installation of the pressure sensitive rubber

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, the pressure sensitive rubber and a fixed value resistor are connected in series in a series circuit whose output voltage is the divided voltage of the pressure sensitive rubber. The divided voltage of the pressure sensitive rubber was obtained to represent the clamping force. According to the fitting curve acquired from the calibration experiment of pressure sensitive rubber, the clamping force is acquired. The maximum friction force is detected by the spring dynamometer which is used to pull the catheter slowly till it beginning 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 is also acquired through doing curve fitting by MATLAB. The relationship curve is shown in the following Fig.10. As shown in the Fig.10, the red curve indicates the relation between the clamping force and the friction force, and the blue one is the fitting curve. The equation (2) acquired from the data detected is shown in the following. It's a cubic equation with one unknown.

$$f_F = 0.038 f_C^{\,3} - 1.295 f_C^{\,2} + 4.318 f_C + 0.0001 \qquad (2)$$

where f_F is the friction force between the catheter and the grasper, f_C is the clamping force, which is acquired by the equation (1) in case of acquisition of voltage of the pressure sensitive rubber. Equation (1)'s accuracy can affect equation (2)'s accuracy through affecting the accuracy of f_C. The equation (2) is used to control the grasper motor according to the clamping force acquired in real time, which can guarantee not to damage the catheter. And the motor can change the clamping force through adjusting the open angle of the two clamping pieces. Due to the character of pressure sensitive rubber, 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 pushing the catheter.

The Fig.11 shows 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.

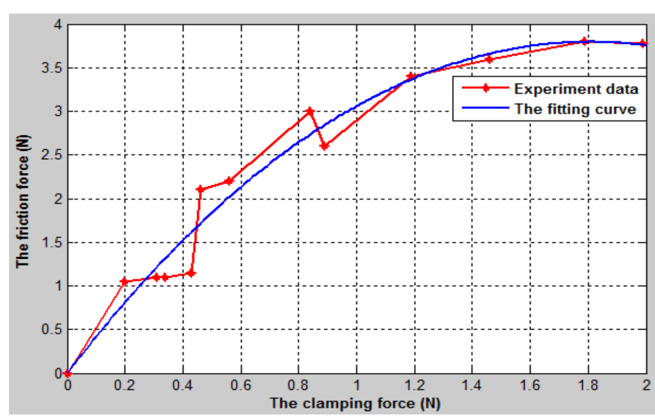

Fig.10 The relationship between clamping force and maximum friction force

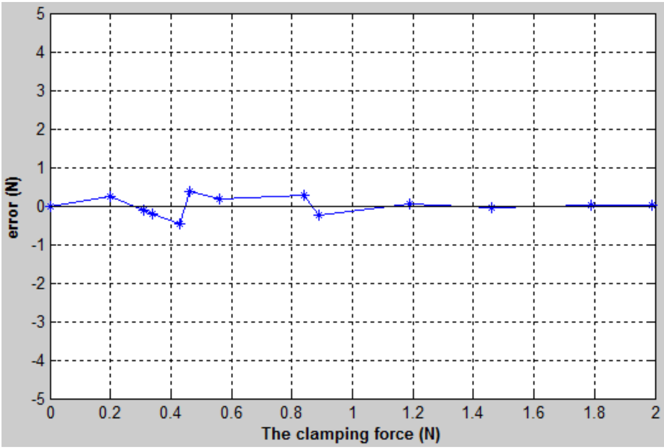

Fig.11 The error between measured value and fitting value of friction force

The maximum clamping force of the grasper is also needed to obtain to guarantee not to damage the catheter. The maximum pressure marked on the package of the catheter is 1100 psi, which is translated into pressure is 64.91N when contact area is a quarter of the whole area of the round tube clamped by the grasper. The Fig.9 can be referred to as a diagrammatic drawing. The diameter of via hole is larger than the catheter when two clamping pieces of the grasper close completely. The grasper can also clamp the catheter when pasted with sponge. And we have done a performance test to make the clamping pieces close completely to clamp the catheter, which is used to observe the damage situation. The catheter is not damaged in the test. The force feedback can protect the catheter from damaging. The operation process is slow, thus, the increasing of contact force will be an incremental process to guarantee finish feedback before damage. So the grasper can satisfy the demand that clamping catheter without relative displacement and damaging catheter.

V. CONCLUSION AND FUTURE WORK

A novel grasper which can imitate the catheter operating action of surgeon's hand has been proposed for a robotic catheter navigation system, 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 use the developed novel robotic catheter system with novel graspers to do the experiments "in vitro" and "in vivo".

ACKNOWLEDGMENT

This research is supported by General Research Program of the Natural Science Foundation of Tianjin (13JCYBJC38600) and the Project-sponsored by SRF for ROCS, SEM and Key Research Program of the Natural Science Foundation of Tianjin (13JCZDJC26200).

REFERENCES

[1] Y. Fu, A. Gao, H. Liu, S. Guo, "The Master-slave Catheterization System for Positioning The Steerable Catheter," International Journal of Mechatronics and Automation," vol. 1, No. 2, pp. 143-152, 2011.

[2] H. Zhao and X. Duan, "Design of a Catheter Operating System with Active Supporting Arm for Vascular Interventional Surgery," 2011 Third International Conference on Intelligent Human-Machine Systems and Cybernetics, pp. 169-172, 2011.

[3] G. Liang and Y. Xu, "Mechanism Design of a Medical Manipulator for Vascular Interventional Surgery," Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 2291-2296, 2011.

[4] J. Zhang, C. Meng, Y. Ma, B. Liu and F. Zhou, "Catheter Localization for Vascular Interventional Robot with Conventional Single C-arm." Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 159-164, 2011.

[5] D. Liu, D. Zhang, and T. Wang, "Overview of the Vascular Interventional Robot," The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 4, No. 4, pp. 289-294, 2008.

[6] R. Beyar, L. Gruberg, D. Deleanu, A. Roguin, Y. Almagor and S. Cohen, "Remote-control Percutaneous Coronary Interventions: Concept, Validation, and First-in-humans Pilot Clinical Trial," Journal of the American College of Cardiology, vol. 47, pp. 296-300, 2006.

[7] N. Xiao, J. Guo, S. Guo, T. Tamiya, "A Robotic Catheter System with Real-time Force Feedback and Monitor," Australas Phys Eng Sci Med, vol. 3, No 35, pp. 283-289, 2012.

[8] L. Da and D. Liu, "Accuracy Experimental Study of the Vascular Interventional Surgical Robot Propulsive Mechanism," Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 412-416, 2011.

[9] H. Zhao, X. Duan, H. Yu and X. Wang, "A New Tele-operating Vascular Interventional Robot for Medical Applications," Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 1798-1803, 2011.

[10]Y. Wang, K. Hu, N. Xiao and S. Guo, "A Force Acquisition Method in A Catheter Navigation System," Proceedings of 2013 ICME International Conference on Complex Medical Engineering, pp. 633-637, 2013.

[11] N. Xiao, L. Shi, B. Gao, S. Guo and T. Tamiya, "Clamping Force Evaluation For A Robotic Catheter Navigation System," Neuroscience and Biomedical Engineering, vol. 1, No. 2, pp.1-5, 2013.

[12] J. Xiong, K. Chen, X. D. Yang, et al, "Accuracy Experimental Study of the Robot-assisted Interventional Therapy System," Mechinery Design &Manufacture, vol. 1, pp. 156-158, 2010.

[13] J. Guo, S. Guo, N. Xiao, X. Ma, S. Yoshida, T. Tamiya and M. Kawanishi, "A Novel Robotic Catheter System with Force and Visual Feedback for Vascular Interventional Surgery," International Journal of Mechatronics and Automation, vol. 2, No. 1, pp. 15-24, 2012.

[14] S. Guo, Y. Gao, J. Guo, Y. Ji and Y. Wang, "Characteristics Evaluation of a Pressure Sensitive Rubber-based Tactile Sensor," Proceedings of the 2013 ICME International Conference on Complex Medical Engineering, pp. 249-253, 2013.

[15] J. Guo, S. Guo, P. Wang, W. Wei and Y. Wang, "A Novel Type of Catheter Sidewall Tactile Sensor Array for Vascular Interventional Surgery," Proceedings of the 2013 ICME International Conference on Complex Medical Engineering, pp. 264-267, 2013.