Proceedings of 2020 IEEE
International Conference on Mechatronics and Automation
October 13 - 16, Beijing, China

A Novel Clamping Mechanism for Circumferential Force Feedback Device of the Vascular Interventional Surgical Robot

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***Abstract* - At present, vascular intervention technique is the most effective way to treat cardio-cerebrovascular diseases. Vascular interventional surgical robot is applied to assist surgeons to done surgical operation effectively, and the study on this kind of robot is become a research hotspot. In vascular interventional surgery, surgeons mainly judge the state of catheter and guide wire in the blood vessel through vision and touch. Therefore, accurate force feedback is helpful for surgeons to operate interventional surgery better. However, most interventional surgery robots focus on the realization of axial force feedback and few robot systems can accurately feedback the circumferential force of the guidewire and the catheter. In this paper, a clamping mechanism for circumferential force feedback device is designed and calibrated. Firstly, the clamping mechanism is designed based on the friction theory and the control method of this mechanism is described in details. Secondly, the calibration methods of the clamping mechanism are proposed. Lastly, the calibration of the mechanism is verified by experiments, and the mechanism is optimized by analyzing the experimental results. The experimental results show that the mechanism can provide an accurate clamping force for the circumferential force feedback device.**

Index Terms* - *Vascular interventional surgical robot, Circumferential force feedback, Clamping mechanism.

I. INTRODUCTION

In general, the prevalence and mortality of cardiovascular diseases in China are still gradually increasing. Cardio-cerebrovascular interventional surgery is a minimally invasive intervention for the treatment of these diseases. It has the advantages of small trauma, low pain and fast recovery which becomes the most effective way to treat cardiovascular and cerebrovascular diseases. During the operation, surgeons usually operate the special catheter, guidewires and other medical devices to the target area through the artery with the assistance of medical imaging instruments and the haptic feedback [1].

In the traditional interventional surgery, surgeons are exposed to radiation for a long time, and wear heavy lead clothing for surgery, which has caused great harm to the health of surgeons [2]. The appearance of vascular interventional surgery robot can reduce occupational hazards of ionizing radiation exposure and orthopedic injury to the interventional cardiologist while offering increased precision and fine control that may confer benefit to the patient [3]. The vascular interventional surgical robot system mainly composed of two parts: the master manipulator and the slave manipulator. When the surgeon operates the master manipulator on the master side, the master manipulator will capture the movement information of the surgeons and send those signals to the slave manipulator though the control unit. The slave manipulator replicates the operation of the surgeons on the slave side, after getting the control signals from the control unit. Meanwhile, the slave manipulator measures the force of catheter and guidewires during the process and send these signals to the master manipulator through control unit. The master manipulator obtains the control signals and reconstructs feedback force for the surgeon [4]-[6]. In this process, surgeons operate the catheter or the guidewire through DSA images, which is used to judge the contacting state of the catheter or the guidewire contacts with the vessel through the resistance [7]. Excessive force between the guidewire and the vessel may result in complications such as inflammation, blood clots, perforation, and hemorrhage [8], [9]. In order to ensure surgical safety, an ideal tele-operated surgery scenario is viewed as a physical extension of the human body [10]. Hence, a high level of transparency is essential, which can help operator to make the correct decision in a human-centered teleoperation system [11]-[13]. Due to the surgeon was physically separated far from the patients, lacking natural haptic sensation is the main limitation in tele-surgery. Therefore, study on the real-time and accurate haptic force feedback is a promising research area in the tele-operated surgery scenario.

In recent years, several research groups have also been devoted to the study of surgical robots with the haptic feedback. A balloon catheter gripping robot that uses a pneumatic actuator was proposed to estimate external force applied to the catheter [14]. A MR fluids-based master haptic interface for providing haptic feedback to the operators via the input catheter manipulation was developed [15]-[17]. In 2018, a novel catheter operating system based on tissue protection to prevent vessel puncture caused by collision was presented [18]. In our previous research, several novel active catheter systems were developed. A vascular international vascular robot with fuzzy control and force feedback was purposed in 2019 [19]. A remote-controlled vascular interventional robot with a novel sensing principle was presented, which can accurately detect and provide force feedback [20]. Meanwhile, a force sensor for the vascular interventional surgery robotic system based on the principle of resistance strain gauge bridge circuit was developed [21]. And the VR-based interventional surgery training system with haptic feedback was developed to train novice surgeons [22]-[24].

During the conventional intravascular interventional procedures, surgeons guide the catheter by two degrees of freedom (pull, push and twist) [25]. Therefore, the force feedback of the guidewire includes axial and circumferential dimensions. The surgeon can judge the state of the collides between the guidewire with the vessel mainly through the axial haptic force. And most interventional surgery robots focus on the realization of axial force feedback, but few robotic systems can accurately feedback the circumferential force of the guidewire and the catheter. However, in order to bring surgeons a stronger sense of surgical presence, an accurate circumferential resistance feedback is indispensable. In some special surgical situations, for example when it is necessary to guide the guidewire through some seriously twisted blood vessels, appropriate circumferential force feedback helps to remind surgeons to slow down the speed of rotating guidewires and avoid scratching the blood vessel wall.

In tele-surgery, the force feedback is provided on the master manipulator by using the force signals measured on the slave manipulator [26]. Therefore, in order to realize the feedback of the circumferential force, two problems need to be solved: how to measure the circumferential force received from the slave manipulator and how to reproduce the circumferential force at the master manipulator. In previous research, a strain sensor is specially designed to detect the small-scale torsional operation torque with low rotational frequency [27]. Therefore, a clamping mechanism is developed to realize the circumferential force feedback of the master manipulator of the vascular interventional surgical robot in this paper. The mechanism converts the driving force of the direct current (DC) motor into circumferential force through worm gear and gear rack. And the mechanism can efficiently adjust the output circumferential force.

The remaining of this paper are organized as follows: In section II, the design and manufacture of the clamping mechanism are proposed and the control method of the clamping mechanism are introduced. And the experiments are designed to calibrate the response time and the accuracy of the clamping mechanism and the results of the experiments are analyzed and discussed in section III. The conclusions of this paper are given in section IV.

II. DESIGN AND MANUFACTURE OF THE CLAMPING MECHANISM

The circumferential force feedback device is a part of the master manipulator of the vascular interventional surgery robot. The device is proposed to realize the accurate reproduction of circumferential force detected from the slave manipulator of surgical robot. The clamping mechanism is the core part of the circumferential force feedback device, which can provide accurate circumferential force to the operator without affecting the axial movement of guidewires. Meanwhile the clamping mechanism adopts the ergonomic design, so that surgeons can obtain the force feedback by manipulating the real catheter and guidewire, which also helps to improve the transparency of surgery [28]. In this way, surgeons are able to apply the experience of interventional operation to control the robot. The remainder of this section describes the hardware design and the control method of the clamping mechanism.

A. *Hardware Design and Manufacture*

The clamping mechanism is divided into two parts: guidewire clamping structure and friction disc clamping structure.

The guidewire is too thin to apply the circumferential force directly. Therefore, a guidewire clamping structure is designed to solve this problem. The image of the guidewire clamping structure is shown in Fig. 1. The guidewire, conical clamp and retractable tube with a friction disc are coaxial. And the thin guidewire is fixed on a light and retractable tube through the conical clamp. As shown in Fig. 1, the retractable tube is divided into inner tube and outer tube. The outer tube has an inner tooth and the inner tube has an outer tooth. The outer tube and the inner tube are sleeved together. Therefore, the retractable tube can transfer the moment in the circumferential direction while sliding in the axial direction. When the outer tube of the retractable tube is subjected to a circumferential force, the force will be transmitted to the clamped guidewire through the inner tube, and the axial movement of the guidewire will not be affected. And the guidewire clamping structure is made from polylactic acid (PLA) material used a 3D printer.

The circumferential force can only be produced when the guidewire is rotating or there is a trend of rotation, which is close to the nature of friction. Therefore, according to the principle of friction, a friction disc clamping structure is designed to simulate the circumferential resistance of the guidewire during operation. The schematic diagram of friction disc clamping structure is shown in Fig. 2.

From the friction formula (1):

$$f = \mu * F_N. \tag{1}$$

where f is the friction force, μ is the friction coefficient and F_N is the pressure force.

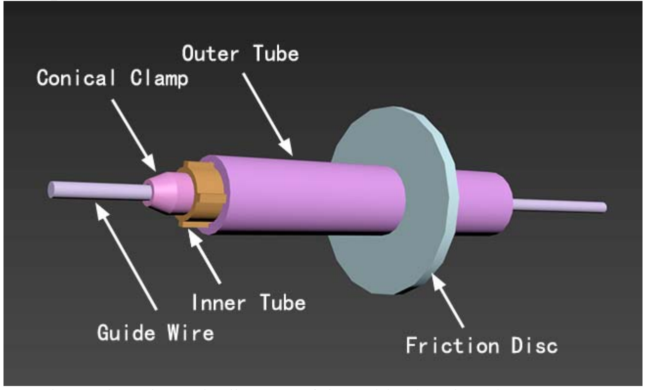


Fig. 1 The schematic diagram of the guidewire clamping structure.

By controlling the pressure force between the friction disc and the friction plate, the circumferential feedback force on the guidewire can be adjusted. The friction force is applied to the friction plate by the motor through the transmission of gear and rack. The relationship between the pressure force on the friction plate and the circumferential moment on the guidewire can be calculated by the following formula (2):

$$\mathrm{M} = \mathrm{L} \times \mathrm{F}. \tag{2}$$

where L is the distance vector from the axis of rotation to the point of application, F is the vector force, and M is moment of force.

During the operation, the motor needs to be started frequently and locked for a long time, which will generate a large current and easily lead to overheating and burning of the motor. Therefore, the purposed mechanism utilizes DC motor for its actuation and the worm is used to realize self-locking after power failure. When the output force reaches the expected value, the motor stops rotating and locks in the current position to ensure the constant output force.

In order to measure the clamping force produced by the clamping structure of the friction plate, a thin film pressure sensor is installed on the friction plate. When the friction disc is clamped by the friction plate, the reaction force of the friction plate will change the output voltage of the film pressure sensor. And a linear voltage converter can convert the output voltage to a voltage from 0 to 3.3V, which is more convenient for A/D converter (ADC) measurement. According to the voltage data measured by ADC, the clamping force can be calculated.

The friction disc clamping structure is shown in Fig. 3. In this figure, the friction plate attached with the thin film pressure sensor is fixed on the shell of the friction plate clamping structure. The other friction plate is fixed on the rack and driven by the DC motor. The friction plates are made from nylon material and this material has outstanding fatigue resistance, even after repeated bending can still maintain the original mechanical strength. And the shell of the friction plate clamping structure is made of acrylic plate cut by laser.

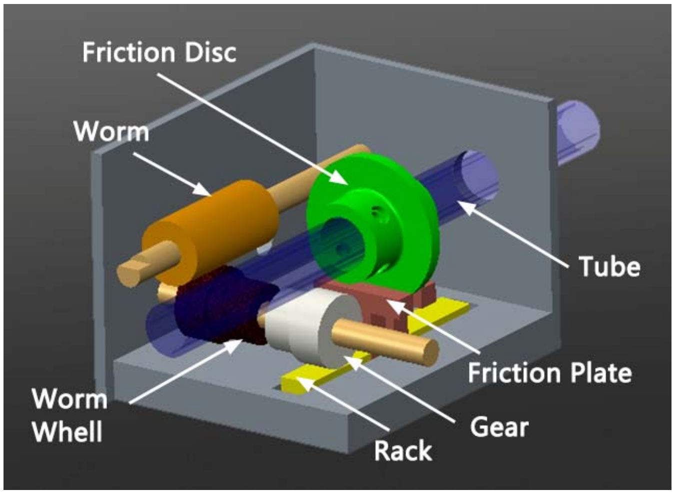
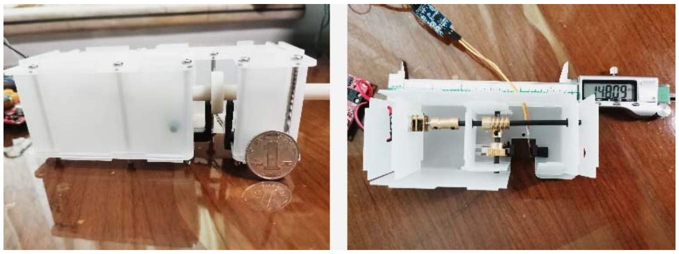


Fig. 2 The schematic diagram of the friction disc clamping structure.



(a) Front view (b) Top view(without cover)

Fig.3 The friction disc clamping structure.

B. Control Method of the Clamping Mechanism

Due to the catheter and guidewire operating force and rotational speed occur on a small scale, the open-loop force feedback structure cannot meet its accuracy requirements. In order to solve this problem, a closed-loop control method is purposed to improve the control accuracy. The experimental system for the clamping mechanism is shown in Fig. 5. The microcontroller (STM32F103) is used to control the clamping mechanism. And the microcontroller communicates with the personal computer through serial port. The thin film pressure sensor, the linear voltage converter and the 24-bit ADC are used for measuring the pressure force generated by the clamping mechanism. The measured pressure force value is used as a negative feedback signal to adjust the output force of the motor.

When the rotation direction of DC motor changes, a large current will be generated, which may burn the motor control board. In order to avoid this situation, a DC motor control method is proposed. The flow chart of the DC motor control method is shown in Fig. 4. Firstly, compare the value of FlagC with the value of FlagB. The value of FlagC represents the current DC motor motion state, and FlagB represents the DC motor motion state in the previous cycle. If the value of FlagC is equal to FlagB, the motor will maintain the current state. Otherwise, brake the motor for 0.1s, and then adjust the rotation direction according to the value of FlagC. Finally, the value of FlagC is assigned to FlagB. In this process, the value of FlagC is determined according to the setting value and the feedback value.

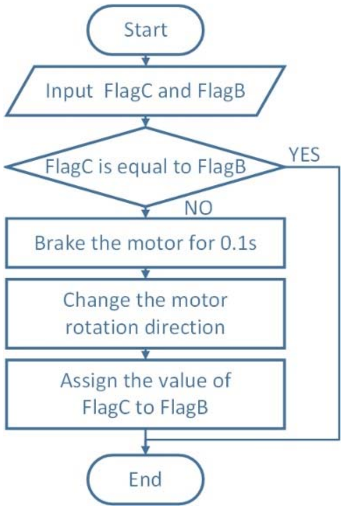


Fig. 4 The flow chart of the DC motor control method.

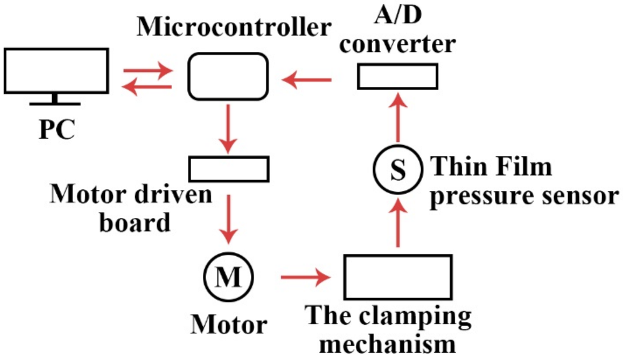


Fig. 5 The experimental system for the clamping mechanism.

Meanwhile, considering the possible abnormal situation in the experiment, an exception handling method is proposed. In this paper, we assume that the pressure force provided by the clamping mechanism is less than 20N. When the input value or feedback value exceeds this range, it is regarded as an abnormal situation. When the abnormal situation occurs, the motor will lock in the current position and send an error report to the personal computer until the abnormal situation is removed. The flow chart of the exception handling method is shown in Fig. 6. In the process of exception handling, the operator can switch to manual mode at any time to operate the DC motor directly.

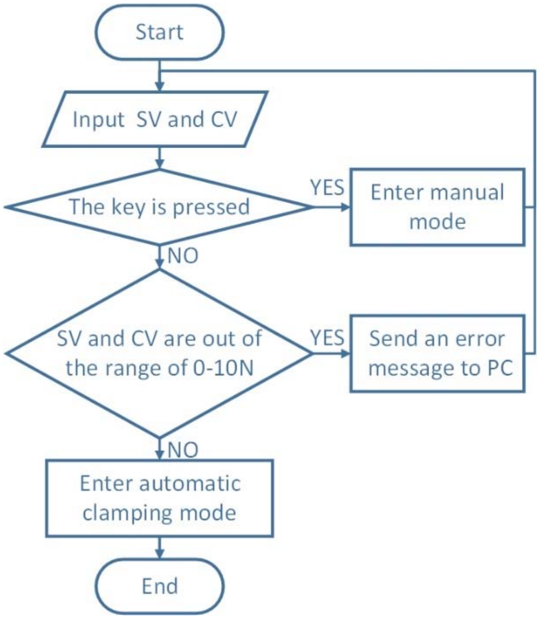
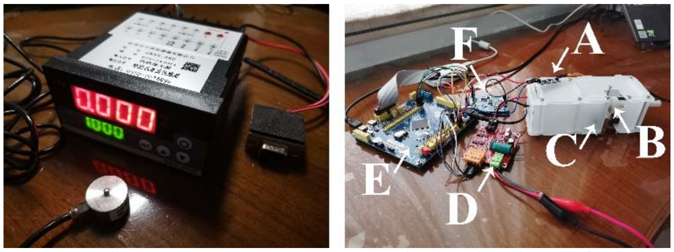


Fig.6 The flow chart of the exception handling method.

III. EXPERIMENTS AND RESULTS

It is difficult to measure the circumferential force on the guidewire directly. Therefore, the circumferential force applied to the guidewire is indirectly measured by measuring the clamping force exerted on the friction disc which is positively related to the circumferential force. And two experiments are designed to calibrate the maximum response time and the accuracy of the clamping force generated by the clamping mechanism. In the experiments, the data sent by the computer to the mechanism is used to simulate the value of the circumferential feedback force sent from the slave manipulator to the master manipulator. And the mechanism for calibration is shown in Fig. 7(a). The accuracy of the pressure force sensor can reach 0.1%, and the sampling rate is 10sps. And the collected data is sent to the personal computer through 485 serial port. The clamping mechanism is shown in Fig. 6(b). In this figure, A is linear voltage conversion module. B is the guidewire clamping structure. C is the friction disc clamping structure. D is the motor driven board. E is microcontroller. And F is 24-bit ADC. The clamping force produced by the clamping mechanism can be measured by replacing the position of the friction disc with the pressure force sensor.



(a) The pressure Sensor (b)The Clamping mechanism

Fig.7 The experimental platform.

A. Calibration of the Clamping Mechanism's Maximum Response Time

Firstly, the range of the output force of the clamping mechanism is calibrated. Then, when the clamping mechanism stably outputs the minimum force, the input data is changed to make the clamping mechanism output the maximum force. The time taken by the clamping mechanism from the minimum stable output force to the maximum stable output force is regarded as the maximum response time. Since the speed of the DC motor is related to the input voltage, the maximum response time of the clamping mechanism under different voltages is also measured. The experimental result is shown in TABLE I.

TABLE I
THE MAXIMUM RESPONSE TIME OF THE CLAMPING MECHANISM

Voltage(V)	Maximum Response Time(s)
3.0	2.76
3.5	2.38
4.0	2.03
4.5	1.74
5.0	2.74
5.5	2.88
6.0	2.63

The experimental results show that the clamping mechanism can output the pressure force from 3 to 20N, and the maximum response time of the clamping mechanism are different under different voltages. The fastest response speed is achieved when the voltage is 4.5V. Limited by the sampling rate of ADC and the processing speed of microcontroller, when the motor speed increases, the output pressure force of the clamping mechanism may vibrate, resulting in the slow response speed of the clamping mechanism. Meanwhile, in order to avoid burning out the motor control board, a 0.1s motor starting delay is added in the control program, which slows down the response speed of the clamping mechanism.

B. Calibration of the Clamping Mechanism's Accuracy

In this experiment, several different input values are set for the clamping mechanism. And the accuracy of the clamping mechanism is calibrated by comparing the error between the theoretical output force and the actual output force. And the experimental result is shown in Fig. 8.

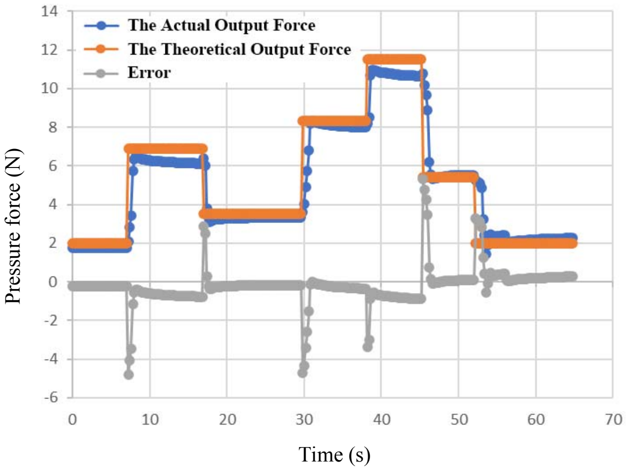


Fig. 8 Experimental results of clamping force output.

The experimental results show that the clamping mechanism can adjust the output pressure according to the input setting value. When the output force of clamping mechanism is stable, the maximum error is 0.881N and the maximum relative error is 16.98%. The main causes of error may be that the output voltage of the thin film pressure sensor is not completely linear with the pressure force. Meanwhile, the feedback signal is easy to be disturbed by external factors in the transmission process, which will also affect the accuracy of the clamping mechanism output force. The friction between the frame and the guide rail and the insufficient fixation of the friction plate and the frame may also cause the output accuracy of the clamping mechanism insufficient.

IV. CONCLUSIONS

In this paper, a clamping structure of friction plate is proposed, which provides a clamping force for the friction disc of the circumferential force feedback device. The experimental results show that the clamping structure can provide the accurate pressure force for the circumferential force feedback device. The maximum error of output force is 0.881N and the maximum relative error is 16.98%. And the maximum response time of the clamping structure is 1.74s, when the voltage is 4V. In the future experiments, the filter algorithm is considered to remove the interference of external factors on the feedback signal. The corresponding compensation algorithm will be designed to improve the accuracy of the output pressure force. Meanwhile, further optimizing the clamping mechanism and using ADC with higher sampling rate to improve the response speed is also the future research plan.

ACKNOWLEDGMENT

This research is partly supposed by National High-tech R&D Program (863 Program) of China (No.2015AA043202).

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