A Vascular Interventional Surgical Robotic System based on Force-Visual Feedback

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***Abstract*— In this paper, based on the previous research of our research team. We proposed a Vascular Interventional Surgical Robotic System based on Force-Visual feedback. In the process of vascular interventional surgery, it is very important to accurately detect the resistance force of surgical catheter, which can improve the safety of operation. Therefore, we developed a force sensor for the vascular interventional surgery robotic system based on the principle of resistance strain gauge bridge circuit. In addition, a complete robotic system with only force feedback is not enough. Therefore, it is necessary to combine the visual feedback interface to complete the operation. Finally, some verification experiments have been completed, including the evaluation experiment of the internal fixture of the force sensor, the calibration experiment of the force sensor, the evaluation experiment of the force sensor, the evaluation experiment of the force feedback, The axial and radial synchronous motion experiment between the master and slave side. Experimental results showed that the feasibility of the force sensor. Vascular Interventional Surgical Robotic System based on Force-Visual feedback has good performance of the force feedback and the synchronous motion between the master and slave side. There is a certain error in the synchronous motion between the master and slave side and the force feedback of the vascular interventional surgery robotic system based on Force-Visual feedback, the error is within the allowable range.**

***Index Terms*—Vascular interventional surgical robotic system (VISRS), force sensor, bridge circuit, visual feedback interface, force feedback.**

I. Introduction

IN recent years, an increasing number of people have caused cardiovascular and cerebrovascular diseases such as coronary heart disease, hypertension, and cerebral thrombosis because of unhealthy lifestyle [1], According to the "Summary of the 2018 report on cardiovascular diseases in China", from 1990 to 2016, the mortality rate of cardiovascular and cerebrovascular disease among urban and rural continued to increase. Besides, it was significantly higher than that of other diseases. At present, the number of cardiovascular and cerebrovascular patients is nearly 290 million in China [2]. Cardiovascular and cerebrovascular diseases have the characteristics of high disability rate, high morbidity and high mortality, which not only affect individual health and quality of life, but also bring extremely heavy economic and spiritual burden to the society and family. It is the biggest killer of national health in China [3]-[4]. With the science and technology development, treatment methods also in gradually upgrade, but it still exists some problems, such as the conventional vascular interventional surgery require a surgeon exposed to X-ray radiation with long time. Therefore, VISRS has widely of application. Many medical research teams at home and abroad have devoted themselves to the study of VISRS, some of the more mature equipment has been put into the market and has been widely used.

In 2014, Institute of Microelectronics (IME) of Singapore, Han Beibei et al, developed a ring-shaped tri-axial force sensor device for a guidewire of the vascular interventional surgery. The force sensor is proved to has the characteristics of high sensitivity, high linearity and no obvious hysteresis [5]. The same year, A new force sensing method is proposed by King's College London, Asghar Ataollahi et al. They have completed the integration of the prismatic-tip optical fibers with a spring structure. The force sensor prototype has simple and compact structure, easy to miniaturize. It has been proved to be capable and feasible of force measurement in the range of 0-2.8N [6]. In 2016, National Cancer Center of Korea, Zhenkai Hu et al, proposed a portable haptic device, which can provide the grasp (kinesthetic) and push–pull (cutaneous) sensations to doctors. This haptic device is applicated for the optical-motion-capture. To verify the usability and dexterity of the proposed haptic device, they have finished the evaluation experiment of haptic device and the needle insertion test. The results showed that the grasp force feedback and the push–pull force feedback provided by the haptic device closely matched with the sensed forces of the slave robot [7]. In 2017, University of Bologna of Italy, Emanuela Marcelli et al, developed a CathROB. The CathROB

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have the key features of extremely compact design, which can minimize encumbrance and time for system set-up in lab. They have reported the evaluation experiments "In vitro and In vivo" of CathROB. Experimental results showed that CathROB has good performance of remote catheter navigation and automatic repositioning [8]. In addition. In 2018, Christopher C Smitson et al, pointed out in the article "Safety and Feasibility of a Novel, Second Generation Robotic-Assisted System for Percutaneous Coronary Intervention: First-in-Human Report" [9]. Compared to the first generation of robotic-assisted system (CorPath 200) [10]-[11], the second generation robotic-assisted system (GRX) simplified equipment exchange, improved functional control, accelerated the rotation of the guidewire. They have reported the second generation robotic-assisted system (CorPath GRX) human experience for the first time. The clinical operation success rate of the system is 97.5%, and the technical success rate of the equipment is 90%. It is safe and effective.

Compared with foreign research, domestic research is in the laboratory stage, but many research teams have achieved good results successively. In 2014, Beihang university, Dangxiao Wang et al, have introduced a method to measure both the translation or rotation of the surgical catheter and push-pull resistance force and rotation resistance torque generated by the contact between the surgical catheter and the vascular wall [12]. In 2018, Shanghai jiaotong university, Kundong Wang et al, proposed a catheter robotic system [13]-[14], The system uses rope-wheel transmission mechanism, and has four operators, which can imitate fours hands of doctors and assistants. Each operator has 3 DOFs (degrees of freedom), namely clamping, rotating and pushing, with a total of 12 degrees of freedom. In addition, they also use distributed control system, real-time coordination of complex motion, and has a high precision. In order to verify the performance of the developed robotic system, they successfully deployed three scaffolds on the live pig. Experimental results showed that the robot has high dexterity, accuracy and practicability, which meets the requirements of intervention surgery. Recently years, the research team led by professor Guo, has also achieved good results in the research on vascular interventional surgery robotic system [15]-[17].

In this paper, we propose a vascular interventional surgical robotic system based on Force-Visual feedback. In order to improve the force detection accuracy of surgical catheter, a force sensor for VISRS based on the principle of resistance strain gauge bridge circuit was designed. In addition, only force feedback is not enough during the operation, Therefore, we completed the verification experiment by combining the visual feedback interface, including the evaluation experiment of the internal fixture of the force sensor, the calibration experiment of the force sensor, the evaluation experiment of the force sensor, the evaluation experiment of the force feedback, The axial and radial synchronous motion experiment between the master and slave side. The structure of this paper is as follows: the first chapter is the introduction, the second chapter is the structure of the VISRS, the third chapter is Force-Visual feedback system, the fourth chapter is experiments and results, the fifth part is discussion, the last part is conclusions and future work.

II. Structure of the VISRS

A. *Overview of the VISRS*

In recent years, many research teams have developed different prototypes of VISRS. However, research on force feedback is still a challenge in this field. Based on previous research by our group [17] [18]. a master manipulator based on the principle of electromagnetic induction is designed to achieve force feedback. Compared with magnetorheological fluid and motor feedback, the method is easy to operate and has no inertia. The method is still in the preliminary research stage. In addition. To ensure the safety of the surgery, this paper combines the force feedback and visual feedback. The whole procedure is shown in Fig.1, it is a closed-loop control system. Surgeons operates the master manipulator on the master side to control the slave manipulator perform the surgery. At the same time, the force between the surgical catheter and the blood vessel wall will be detected and transmitted to the master manipulator to form force feedback. An Internet Protocol (IP) camera (TE40, Huawei technologies co., LTD., China) is used to monitor the surgical scene in real time to form visual feedback.

B. *Master Manipulator*

As shown in Fig.2, the structure of the master manipulator. The permanent magnet is used to produce a uniform magnetic field. When an electric coil is used to cut magnetic lines under the action of a permanent magnet, an electromagnetic force is generated. This electromagnetic force is fed back to surgeons' hand as a feedback force through the operation catheter. In the previous research of our research team [18], the experiment of calibration between the electromagnetic force and current has been completed.

The operation catheter has two DOF (degrees of freedom) and is operated by a surgeon, one is axial motion, and the other is radial motion. Therefore, a solid shaft photoelectric encoder (ZSP3806-2500BM, Jinan ke sheng automation technology co. LTD., China) and a hollow shaft photoelectric encoder are used to acquire the motion information (push-pull or rotation) of the

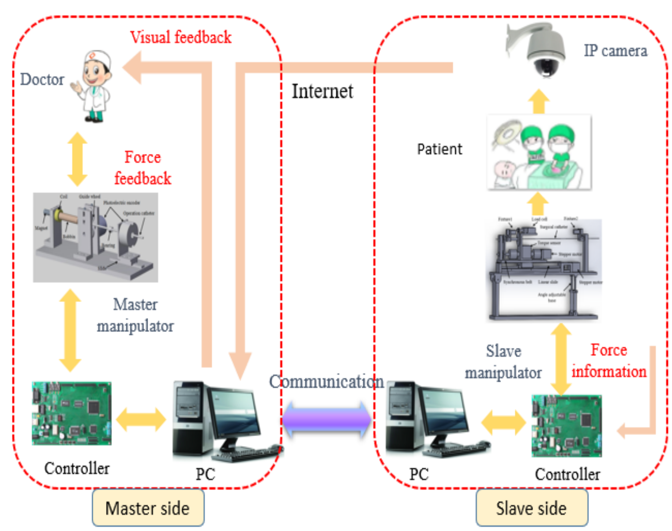


Fig. 1. The conceptual diagram of the VISRS

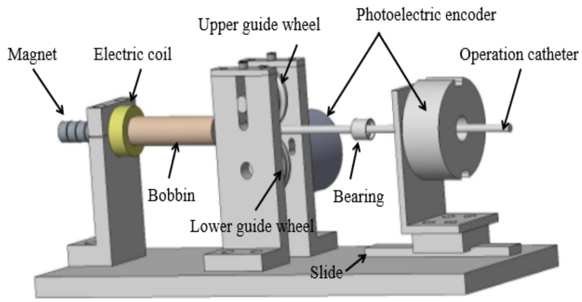


Fig. 2. The structure of the master manipulator

operation catheter. In addition, under the action of the spring, the upper guide wheel and the lower guide wheel squeeze each other and clamp the operation catheter to reduce sliding friction, thus reducing the generation of errors.

C. Slave Manipulator

The structure of the slave manipulator is shown in Fig.3. This slave manipulator not only drive the movement of the surgical catheter, but also detect the force information of the surgical catheter in real time and feed back to the master side.

A load cell (TU-UJ5N, TEAC, Tokyo Japan) is used to detect the resistance force of the surgical catheter during the operation. The output signal of the load cell is transmitted to the Analog-to-Digital conversion (AD) module after the amplifier circuit to realize the data collection, the load cell can detect the maximum thrust of +5N and the maximum tension of -5N.

A stepping motor (AR24SAKD-N10-1, Tianjin yat bochi technology Co. LTD., Tianjin, China) is connected to the linear screw module for the forward and backward movement of the surgical catheter. In this system, the stepping motor parameters are as follows: the resolution is 1000 p/R, the reduction ratio is 100, the angle of one pulse of the stepping motor is 0.0036 degrees. The length of the screw module is 400 mm. It consists of a ball screw and a slider. It can convert the radial movement of the stepping motor into forward and backward movement of the catheter. Another stepping motor drives the synchronous belt to realize the rotation of the surgical catheter.

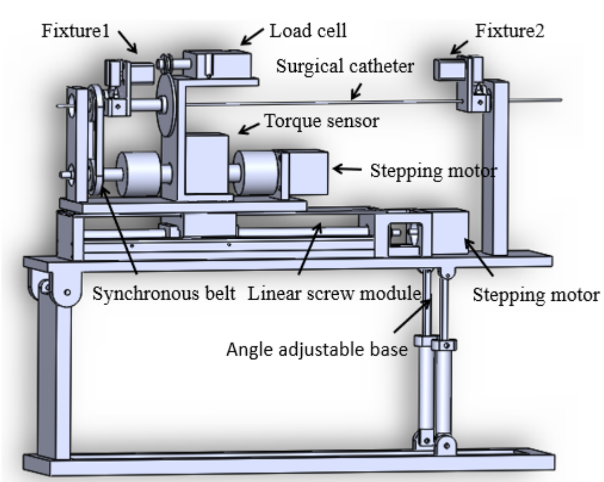


Fig. 3. The structure of the slave manipulator

III. Force-Visual Feedback System

As shown in Fig.4. The VISRS includes force feedback and visual feedback. Force feedback system and Visual feedback system are introduced respectively in Part B and Part C of this chapter. Force feedback system and visual feedback system are important components of the VISRS. Both are indispensable. The force feedback system detects the force information of the surgical catheter in real time and feeds it back to the master side accurately. The master manipulator reproduces the force and actions on doctors' hand. the visual feedback system intuitively feeds back the motion information and force information of the surgical catheter to the doctor in the form of a digital-to-shape combination. In the simultaneous action of force feedback and visual feedback, the safety of surgery is guaranteed.

A. Design of a Force Sensor for VISRS

1) The design principle of the force sensor

The bridge circuit of resistance strain gauge can be divided into single arm, double arm and full bridge. The output of single arm measurement circuit is minimum, linear and stability are poor. The output of double arm measurement circuit is twice that of single arm measurement circuit. The output signal of the full bridge measurement circuit is four times that of the single arm measurement circuit, the performance is the best. Therefore, we use the full bridge circuit measurement method to design the force sensor.

Fig.5 (a) shows the single arm measurement circuit, Fig.5 (b) shows the full bridge measurement circuit.

For the single arm measurement circuit:

$$U_0 = \left[\left(\frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2} \right) - R_4 / \left(R_4 + R_3 \right) \right] \times U_i \quad (1)$$

Set R_1=R_2=R_3=R_4 =R, $\Delta R_1/R_1$= ΔR/R<<1, ΔR/R = $K\varepsilon$, K is the sensitivity coefficient (K=2.0±1%). So. U_0=(1/4)×$K\varepsilon$×U_i. Similarly, for the full bridge measurement circuit: U_0=$K\varepsilon$×U_i.

The proposed force sensor is designed based on the principle of the full bridge measurement circuit, as shown in Fig.5 (b). When no force is applied, the strain is 0. The output voltage of the full bridge measurement circuit is 0, namely, the balance of the full bridge circuit. It can be seen from the balance condition of the full bridge measurement circuit that the initial resistances R_1, R_2, R_3, and R_4 of the four bridge arms should satisfy $R_1R_3 = R_2R_4$, or $R_1/R_2 = R_4/R_3$, usually R_1 is equal to R_2 is equal to R_3 is equal to R_4.

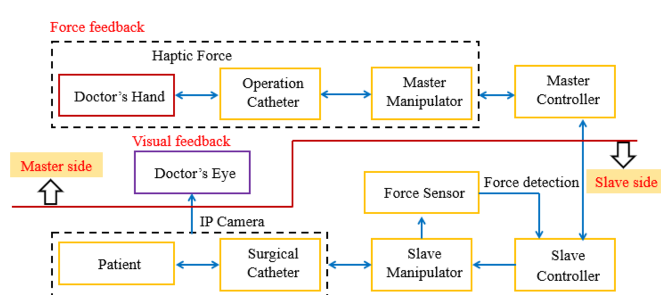
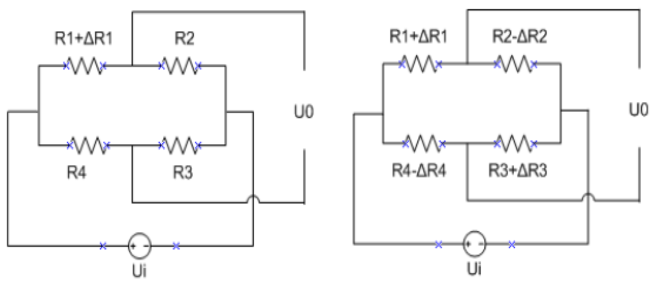


Fig. 4. The Force-Visual feedback system



(a) (b)

Fig. 5. The schematic diagram of the bridge circuit.

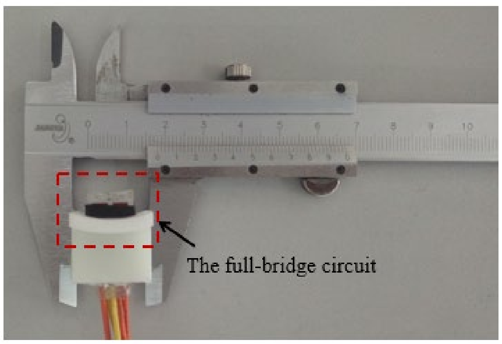


Fig. 6. The physical map of the full-bridge circuit

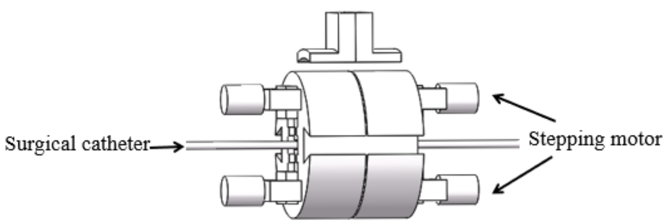


Fig. 7. The internal structure of the proposed force sensor

The input voltage U_i remains constant while the full-bridge circuit is working. When the value changes ΔR_i of four bridge arm resistance is far less than the initial resistance, and bridge load resistance is infinite, the output voltage U_0 of the bridge can be approximately expressed in the following formula [19].

$$U_0 = \left[\frac{R_1 \times R_2}{(R_1 + R_2)^2} \times \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \right] \times U_i \tag{2}$$

Since R_1 is equal to R_2 is equal to R_3 is equal to R_4, it can be changed as:

$$U_0 = \frac{U_i}{4} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \tag{3}$$

Set $\Delta R_i/R_i = K \times \varepsilon$, K is the sensitive coefficient, ε is the strain of the resistance strain gauge. Therefore, the formula (3), it can be written as:

$$U_0 = \frac{K}{4}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \tag{4}$$

In this design, the value of the resistance strain gauge is 120Ω, the power supply voltage 3-10V, the mechanical lag is 1.2um/m. The physical map of the force sensor is shown in Fig.6.

2) The structure design of the force sensor

The internal structure of the proposed force sensor is shown in Fig.7. It consists of 4 stepping motors, two types of slider and supporting structures.

The principle of releasing and clamping the surgical catheter is shown in Fig.8 (a), when the stepping motor rotates, the slider 1 connected with the guide screw moves in the up and down directions, squeezing the slider2 so that the slider2 moves in the left and right directions. Two sliders2 had relative motion and clamping or releasing the surgical catheter. The release of the surgical catheter is realized by adding the spring between the slider2. To increase the friction between the surgical catheter and the slider2 and reduce the relative sliding of them, a special treatment was carried out for the slider2, as shown in Fig.8 (b).

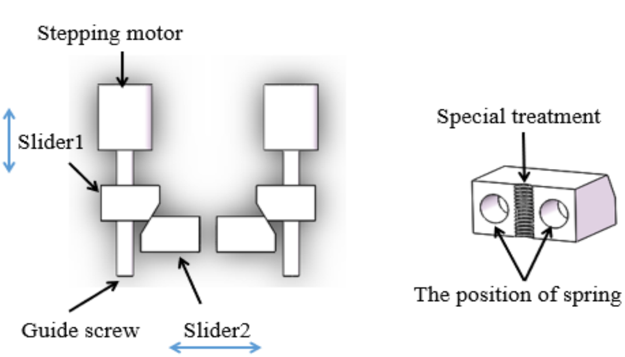
3) The measuring principle of the force sensor

Fig.9 shows the overall structure of the proposed force sensor, including the internal structure and the external structure. The surgical catheter and the internal structure form a whole under the action of the stepping motor. When the internal and external structure moves in the opposite direction, the full-bridge circuit outputs a weak voltage signal, which is amplified by amplifier module and collected by AD data acquisition card (USB2831, Beijing altai technology development co. LTD, Beijing, China). The proposed force sensor must be calibrated using a standard load cell (TU-UJ5N, TEAC, Tokyo, Japan) before application. The calibration experiment of the force sensor is introduced in detail in the next part.

4) The evaluation experiment of the internal fixture of force sensor

Before using the proposed force sensor, we need to determine the performance of the internal fixture device of the force sensor and determine whether the fixture can hold the surgical catheter without damaging the surgical catheter. At the same time, we need to measure the maximum static friction force between the surgical catheter and the internal fixture of the force sensor. The experimental process is shown in Fig.10.

An axial thrust is applied to the surgical catheter through a load cell, the thrust is continuously increased until the fixture device slips relative to the surgical catheter. Then, the sampling frequency of the AD data acquisition card in the experiment is 50000Hz. The experiment results is shown in Fig.11.



(a) (b)

Fig. 8. The principle of releasing-clamping the surgical catheter.

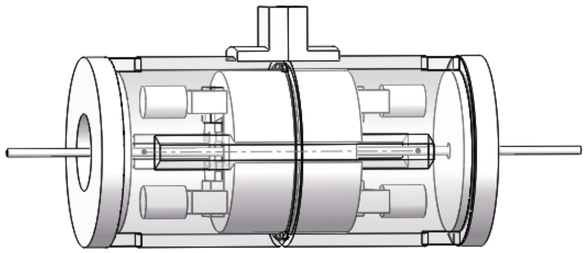


Fig. 9. The overall structure of the proposed force sensor

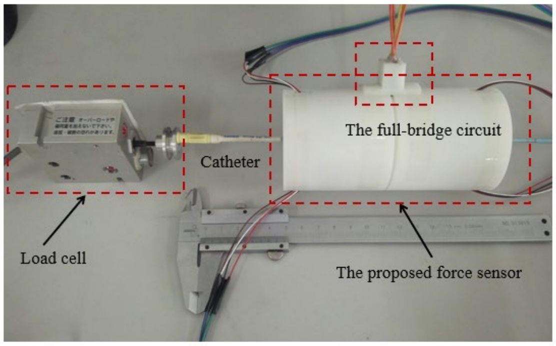


Fig. 10. The internal fixture of force sensor evaluation experiment

As can be seen from Fig.11, when the thrust of the surgical catheter reaches 1500mN, the thrust drops sharply, indicating that the surgical catheter and the fixture have relative sliding at this time. Previous studies [20] have shown that the resistance force of the surgical catheter is far less than 1500mN in the process of simulation experiments "In vitro", proving that the internal fixture device of the proposed sensor is effective.

5) The calibration experiment of the force sensor

The calibration experiment process of the proposed force sensor is similar to the evaluation experiment of the internal fixture of force sensor. The axial thrust (Below 1500mN, ensure that the surgical catheter and fixture do not slide relative to each other) is applied to the surgical catheter through the load cell. Experimental results as shown in Fig.12.

As shown in Fig.12, with the increase of axial thrust of the surgical catheter, the output voltage of the force sensor also increases. The formula is as follows:

$$F = 0.7022U_0 + 933.6 \tag{5}$$

Where, F is the axial thrust acting on the surgical catheter, and U_0 is the output voltage of the proposed force sensor. From references [21], we can know that the strain and resistance force of the resistance strain gauge shows a linear relationship, and the non-linear relationship between strain value and resistance change will be shown when the resistance strain gauge is under a large strain. And in our calibration experiment, the axial thrust applied to the surgical catheter was in a linear range. when U_0=0, F=933.6mN, because the force sensor is 3D printed, and there will be certain error in the printing accuracy and the selection of materials. Therefore, in future experiments, the output value of the force sensor needs to be subtracted 933.6mN, which is the actual force value of the surgical catheter.

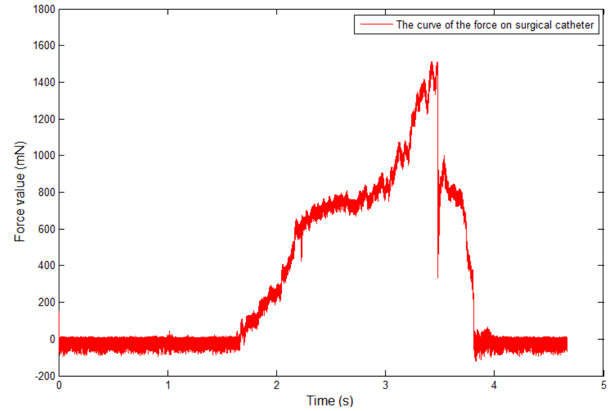


Fig. 11. The results of internal fixture of force sensor evaluation experiment

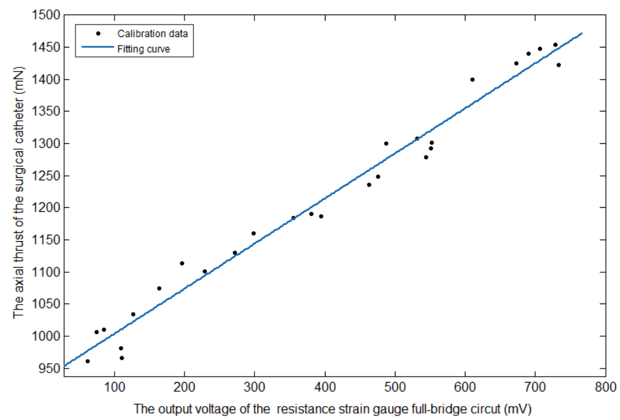


Fig. 12. The results of the calibration experiment of the force sensor

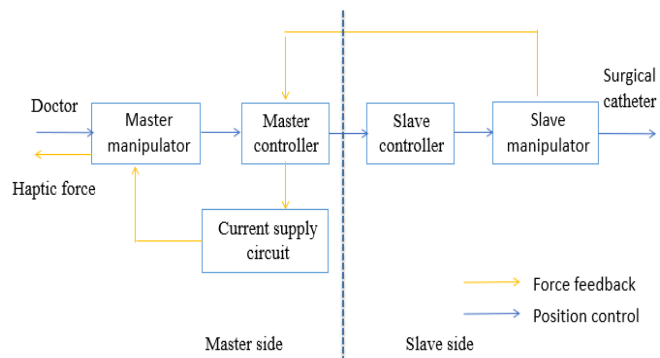


Fig. 13. The block diagram of force feedback

B. Force Feedback System

The force feedback refers to the force information of the surgical catheter is transmitted to the master side. The master manipulator generates an equal force and then transmits to the doctor's hand by the operation catheter. Fig.13 shows the block diagram of the force feedback. Our research team adapts the principle of electromagnetic force to achieve force feedback.

Based on previous studies in our research team [18], we can get the relationship between electromagnetic force (F) and input current (I), namely:

$$F = -290I^2 + 556I \tag{6}$$

C. *Visual Feedback Interface*

VIS is a complicated surgical technique. But over the years, through the unremitting efforts of various research teams, there has been a breakthrough in the research of the force feedback. However, for complex VIS, only force feedback is not enough. It is necessary to systematize multiple discrete information and provide to the doctor in the form of visual feedback. Therefore, we used LabView programming language to develop a visual feedback interface for the master-slave vascular interventional surgery robotic system. As shown in Fig.14. The main functions of the force information display unit of the surgical catheter and the movement information display unit of the operation catheter is to present the force information and movement information of the catheter to the doctor in real time in the form of Numbers and graphics. The main function of the safety warning area is to inform the doctor whether the current operation is safe by switching between the green light, yellow light and red light.

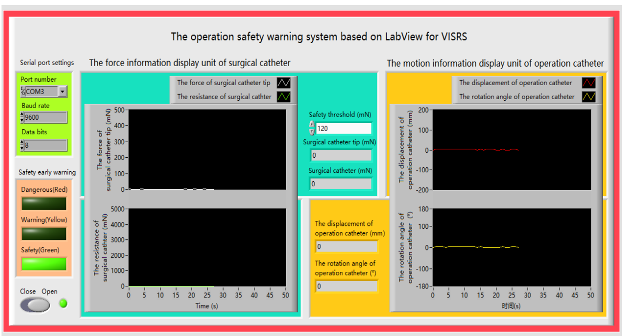


Fig. 14. The operation safety warning system

IV. Experiments and Results

The blood vessel model used in the experiment is shown in Fig.15. The inner diameter is 7mm, the outer diameter is 11mm.

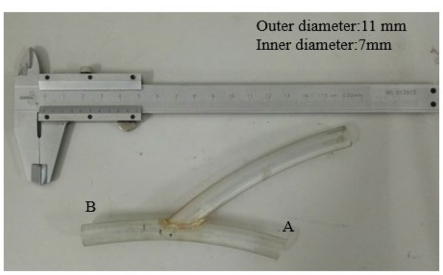


Fig. 15. The blood vessel model used in the experiment

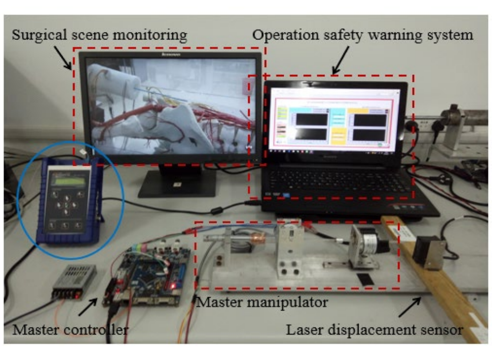


Fig. 16. The master side of VISRS based on Force-Visual feedback

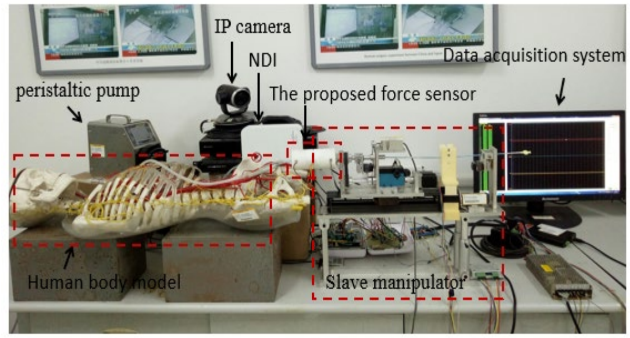


Fig. 17. The slave side of VISRS based on Force-Visual feedback

Fig.16 shows the master side of the vascular interventional surgery robotic system based on Force-Visual feedback. There is surgical scene monitoring interface, operation safety warning system, master controller, master manipulator and so on.

Fig.17 shows the slave side of the vascular interventional surgery robotic system based on Force-Visual feedback. There is IP camera, peristaltic pump, slave manipulator, the proposed force sensor, human body model, NDI electromagnetic tracking system, data acquisition system.

The experimental process: We installed the proposed force sensor on the front of the slave manipulator (as shown in Fig.17). The staff operates the master manipulator and controls the slave manipulator to push the surgical catheter from the position A of the vascular model used in the experiment (as shown in Fig.15) to the position B, the experiment was conducted for 90 seconds. Experimental data was obtained, which will be analyzed in the part A, part B, part C and part D.

A. *The evaluation experiment of the proposed force sensors*

The experimental results as shown in Fig.18, the output curve of the proposed force sensor is basically consistent with that of the load cell. However, the force sensor also showed obvious hysteresis. The reason for this phenomenon is that the force sensor is 3D printed, and there will be certain deviation in the printing accuracy and the selection of materials. The proposed force sensor is in the preliminary design stage. In the future research work, we will develop an algorithm to overcome the problem of the hysteresis.

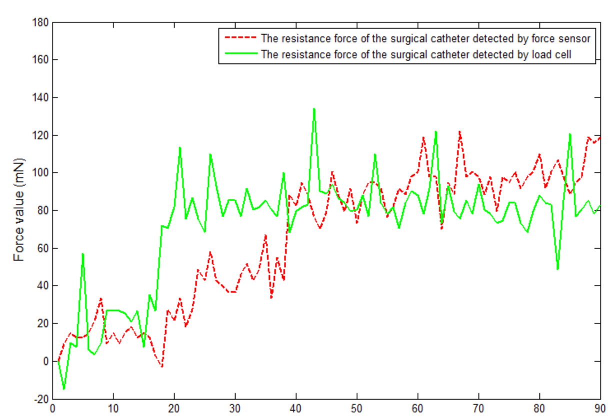


Fig. 18. The resistance force detected by force sensor and load cell

B. The evaluation experiment of the force feedback

As shown in Fig.19 and Fig.20, respectively, the comparison curve between detection force and feedback force and the error curve between detection force and feedback force.

As shown in Fig.19, compared the experiment began with ended, the force of the surgical catheter was increased. Because the effect of the circulation flow of the intelligent peristaltic pump, as well as the impact of friction between the lateral wall of the surgical catheter and the inner wall of the vascular model, prevents the surgical catheter from moving forward.

However, there is a certain error between the detection force of the slave side and the force generated by the electromagnetic induction damper of master manipulator (<20mN), as shown in Fig.20. This error may be caused by electromagnetic losses, we will improve it in future studies.

C. The axial synchronous motion experiment between the master and slave side

Fig.21 shows the electromagnetic tracking system (Aurora electromagnetic tracking system, NDI, Canada). It is composed of a system control unit, a magnetic field generator, a sensor interface unit and an electromagnetic sensor. Its function is to locate the surgical catheter and obtain the position information of the surgical catheter in real time.

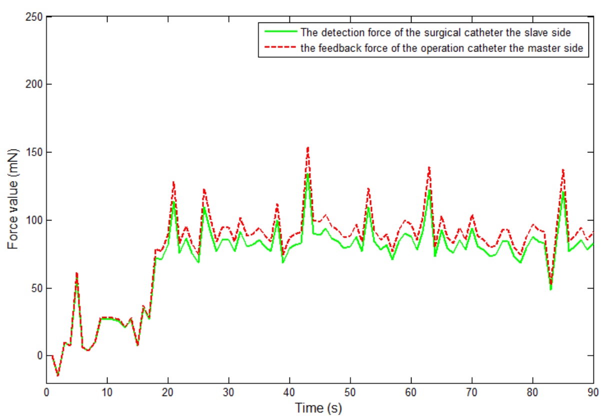


Fig. 19. The comparison curve between detection force and feedback force

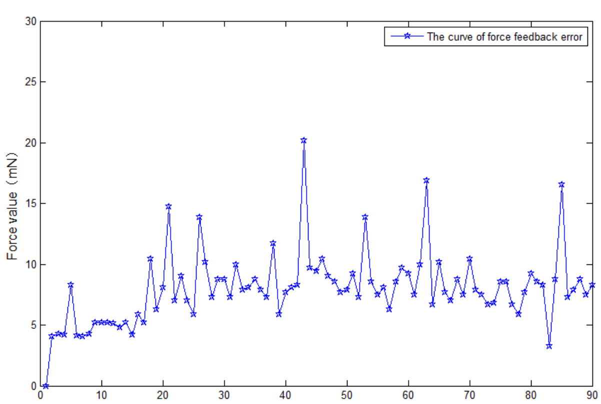


Fig. 20. The error curve between detection force and feedback force

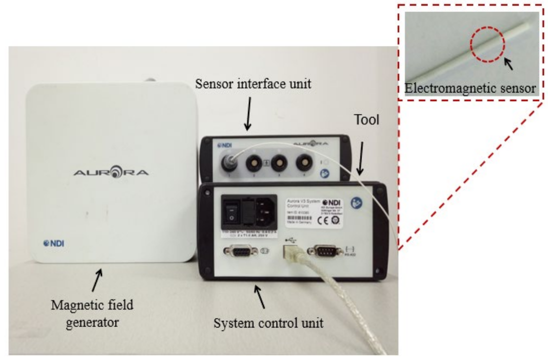


Fig. 21. The electromagnetic tracking system

As shown in Fig.22, Fig.23, Fig.24, respectively, the axial movement trajectory of the master and slave side, the position of the catheter of the master and slave side and the position error of the catheter of the master and slave side.

It can be seen from Fig.24 that the axial synchronous motion error of the master and slave side is maintained between plus and minus 1.2mm. This error occurs because the "trembling" of the hand will be detected. In addition, there is also a certain error between the mechanical structure of the master and slave manipulator, which is inevitable. In the current study, other research teams proposed ways to overcome the "trembling" of human hands [22].

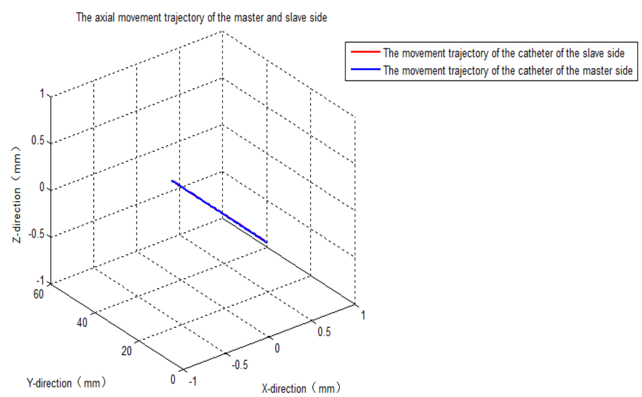


Fig. 22. The axial movement trajectory of the master and slave side

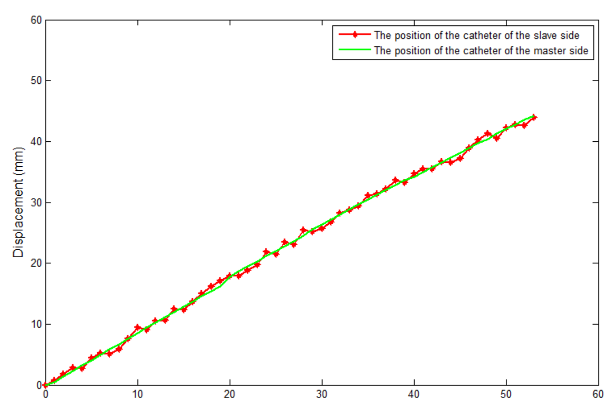


Fig. 23. The position of the catheter of the master and slave side

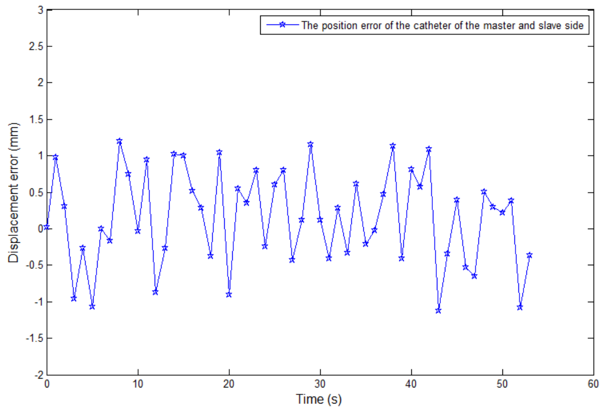


Fig. 24. The position error of the catheter of the master and slave side

D. The radial synchronous motion experiment between the master and slave side

As shown in Fig.25, Fig.26, Fig.27, respectively, the radial movement trajectory of the master and slave side, the position of the catheter of the master and slave side and the position error of the catheter of the master and slave side.

As shown in Fig.27. It is the radial synchronous motion error of the master and slave side, which is maintained between plus and minus 2.5 degrees. The tracking error is inevitable, such as the "trembling" of the hand, mechanical structure and so on.

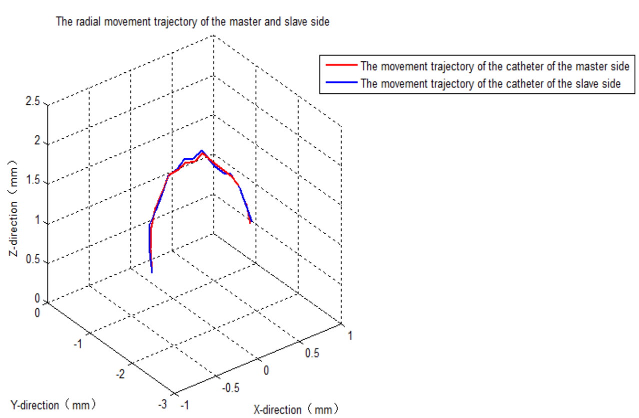


Fig. 25. The radial movement trajectory of the master and slave side

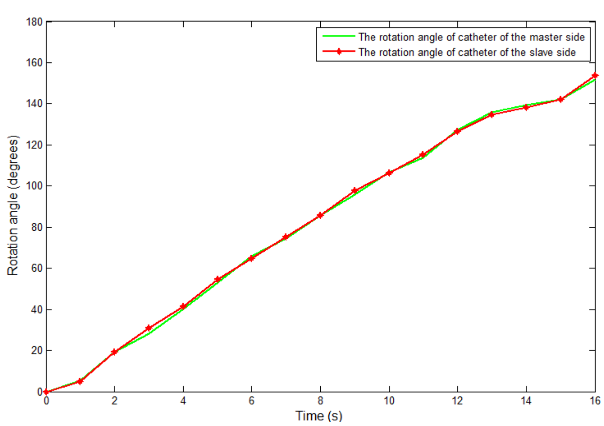


Fig. 26. The rotation angle of the catheter of the master and slave side

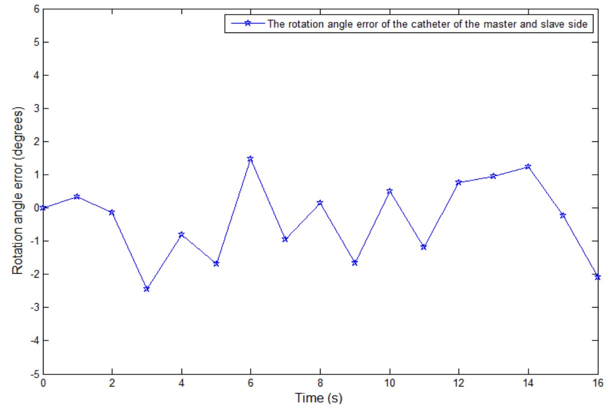


Fig. 27. The rotation angle error of the catheter of the master and slave side

V. DISCUSSIONS

Experimental results showed that (1) when the axial thrust of surgical catheter was greater than 1500mN, the surgical catheter and the clamping device of force sensor would slide relatively. (2) the output curve of the proposed force sensor is basically consistent with that of the load cell, but the force sensor also showed obvious hysteresis. The reason for this phenomenon is that the force sensor is 3D printed, and there will be certain deviation in the printing accuracy and the selection of materials. (3) the resistance of the surgical catheter of the slave side and the electromagnetic force generated by the electromagnetic induction damper of the master side have a certain error (less than 20mN), this error may be caused by the electromagnetic loss. (4) the axial synchronous motion error of the master and slave side is maintained between plus and minus 1.2mm, the radial synchronous motion error of the master and slave side is maintained between plus and minus 2.5 degrees. According to the clinical application report of vascular interventional surgery robot [23], the error is within the allowable range.

VI. CONCLUSIONS AND FUTURE WORK

This paper proposed a vascular interventional surgical robotic system based on Force-Visual feedback. In order to improve the force detection accuracy of surgical catheter, a force sensor for VISRS based on the principle of resistance strain gauge bridge circuit was designed. Besides, combined with visual feedback system. We have completed some verification experiments, including the evaluation experiment of the internal fixture of the force sensor, the calibration experiment of the force sensor, the evaluation experiment of the force sensor, the evaluation experiment of force feedback, the axial synchronous motion experiment of the master and slave side, the radial synchronous motion experiment of the master and slave side. Experimental results showed that the effectiveness of the internal fixture of the force sensor and the feasibility of the proposed force sensor. the resistance force of the surgical catheter of the slave side and the electromagnetic force generated by the electromagnetic induction damper of the master side have a certain error (less than 20mN). The axial synchronous motion error of the master and slave side is maintained between plus and minus 1.2mm, the radial synchronous motion error of the master and slave side is maintained between plus and minus 2.5 degrees.

In the future research, the VISRS will be used to complete live animal experiments under the extent permitted by law to verify the authenticity and reliability.

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