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Preliminary Method for Reducing Contact Force between Catheter Tip and Vessel Wall in Endovascular Surgery

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***Abstract* - The study of force has always been very important in robot-assisted vascular interventional surgery. In some special environments, the blood vessels are more curved, and it is difficult for the catheter to pass through smoothly, even with the guidance of the guidewire. However, this will cause excessive contact force between the tip of the catheter and the blood vessel wall, affecting the safety of the operation. Therefore, in this paper, a preliminary concept was proposed to reduce the contact force between the tip of the catheter and the blood vessel wall. Besides, a magnetic field generator was integrated in the slave side of the system, and it can generate a magnetic field to assist the deflection of the tip of the catheter in the more curved blood vessel. Finally, the experiment was carried out to evaluate the proposed method, and the results were indicated that the electromagnetic force can deflect the tip of the catheter effectively, the tip of the catheter can pass through the more curved blood vessel with relatively small contact force in the presence of the magnetic field. So, we can draw the conclusion that the concept proposed in this paper is reasonable and effective.**

Index Terms – Robot-assisted Vascular interventional surgery. Contact force. Uniform magnetic field. Electromagnetic force.

I. INTRODUCTION

Recently, the robot-assisted vascular interventional surgery has attracted more attention due to their good stability and high accuracy. However, in the traditional interventional surgery, to prevent doctors from being exposed to X-ray radiation, doctors need to wear the radiation protective clothing and complete the complex surgical operation in the operating room, which easily fatigue the doctors, resulting in misoperations and affecting the safety of the operation. Compared to traditional interventional surgery, the robot-assisted vascular interventional surgery can separate doctors from the operating room, prevent doctors from being exposed to X-ray radiation and reduce the burden on the surgeon. Therefore, the research of the robot-assisted vascular interventional surgery has good significance.

Nowadays, with the unremitting efforts of many scientific research groups, robot-assisted vascular interventional surgery has been greatly improved. For instance, to improve the tactile presence of the robot-assisted system and reduce the fatigue of doctors during the operation, the robot-assisted system with the function of haptic force feedback was developed based on MR (Magnetorheological) fluids [1]-[5], and the inspiration comes from the change of MR fluids under the action of the magnetic field. Besides, there is also a method of using torque properties of the motor to achieve the haptic force feedback of the system [6][7]. To separate doctors from the operating room and reduce the fatigue of surgeons during the operation, the robot-assisted system was designed in a master-slave structure, for instance, a vascular interventional robot was developed by the group form Beijing Institute of Technology [8]-[12], it has been evaluated by the experiments in human in 2018; A vascular intervention robot system for operating the steerable catheter was developed by the group from Hanyang University [13]; An endovascular intervention robot with multi-manipulators was developed by the group form Shanghai Jiao Tong University [14]; A surgeon augmented endovascular robotic system was developed by the team from University of Illinois at Urbana-Champaign [15]. To improve the human-machine interaction ability of the system, a non-contact detection method was presented to assist the doctor in performing the operation [16]; An interface was proposed to provide the visual feedback for the surgeons [17]. To improve the precision, the stability, and reduce the procedural duration of the system, the deep reinforcement learning technology was applied to the current research to realize supervised semi-auto nomous control [18]-[20]. Besides, some algorithms have been developed to reduce the varying time-delay [21] and minimize the backlash occurrence during vascular interventional surgery [22]. But the natural behaviour analysis of the interventionalist and the motion pattern recognition of the guidewire are rarely involved in percutaneous coronary intervention. Therefore, an analysis framework was proposed by a group from University of Chinese Academy of Sciences [23]. To control the position and posture of surgical instruments, the magnetic actuation was applied to the robot-assisted system, and some results indicated that the magnetic drive has the advantages of not requiring the repositioning of the patient [24] and increasing the intervention speed of the robot-assisted system [25].

In addition, some of the robot-assisted systems have been applied in clinical practice, and their surgical reports have been published. For instance, (1) Magellan medical vascular catheter control system (VCCS) [26]; (2) Sensei X™ robotic navigation system (RNS) [27]; (3) CorPath GRX robotic-assisted system [28]; (4) Amigo™ system [29]; (5) Niobe magnetic navigation system [30].

Although the research on robot-assisted systems has made considerable achievements, there are still some challenges that need to be tried and improved. For instance, in the more curved blood vessel environments, the tip of the catheter is difficult to correctly choose the target blood vessel branch, which makes it difficult for the doctors to operate; Moreover, the contact force between the tip of the catheter and the blood vessel wall is too large, which affects the safety of the surgery. Therefore, based on the above challenges, the main contribution of this study is to propose a preliminary method for reducing the contact force of the tip of the catheter, ensuring the safety of the surgery, and avoiding the puncture of blood vessels by integrating magnetic field control into the slave side of the robot-assisted system. Its main principle is to realize the deflection the tip of the catheter in the extremely curved blood vessel environments during the operation.

The remainder of this paper is as follows; In Section II, the proposed robot-assisted system is descripted. In Section III, the methods of the magnetic field control and the deflection of the tip of the catheter is described. In Section IV, the comparative experiments are carried out, the experiment results are obtained and discussed. In Section V, the conclusion is drawn.

II. System Description

Fig.1 is the preliminary concept of a robot-assisted system integrated with a magnetic field generator at the slave side. The developed system adopts a master-slave design concept, and its purpose is to separate the doctor from the operating room and guarantee the safety of doctors. In addition to being responsible for the collection and transmission of the surgical actions, the master side also needs to have the function of tactile force feed back to enhance the transparency of the developed system. The master side mainly includes the master manipulator developed by our previous studies [1][2][4][31], a surgeon with extensive experience. And the slave side is responsible for receiving and executing the information come from the master side, realizing the position and force feedback. The slave side mainly includes an internet protocol camera, a magnetic field generator, a slave manipulator, and a patient. The magnetic field generator is used to provide a magnetic field, apply an electromagnetic force on the tip of the catheter, assist the tip of the catheter pass through the blood vessel smoothly, and reduce the contact between the tip of the catheter and the vessel wall. In addition, the internet protocol camera is adopted to realize the visual feedback of the proposed robot-assisted system. So, the safety of the proposed robot-assisted system can be improved through the combination of the force-visual feedback.

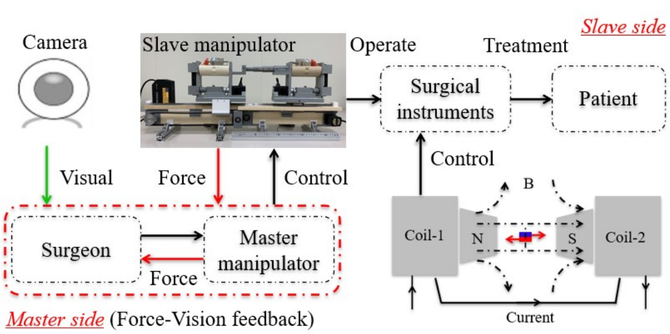


Fig. 1 The robot-assisted system integrated with the magnetic field generator.

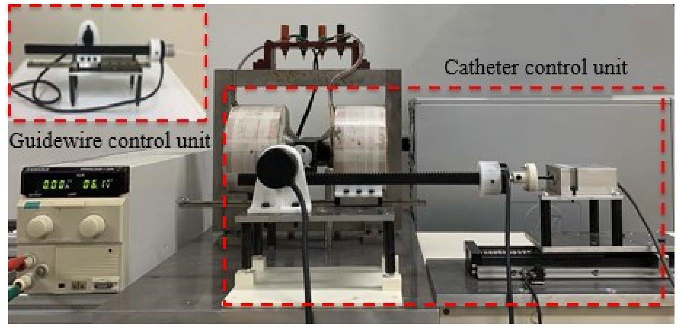


Fig. 2 The master manipulator of the robot-assisted system.

A. The Master Manipulator

Fig.2 is the master manipulator, its function of haptic force feedback was realized by the MR fluids. A catheter control unit was used to control the catheter manipulation unit of the slave manipulator, which includes a magnetic field generator for the change of the state of the MR fluids, two encoders (MTL, ME S020-2000P, Japan) for the collection and transmission of the surgical actions, and a load cell (TU-UJ5N, TEAC, Japan) for the measurement of the haptic force that applied on the doctor's hand. Besides, a guidewire control unit was used to control the guidewire manipulation unit of the slave manipulator. And the principle is similar to the catheter control unit, two encoders are used to collect and transmit the doctor's surgical actions.

The haptic force feedback of the master manipulator is an important part for the improvement of safety of the system, the inspiration comes from the change of the MR fluids under the action of the magnetic field. The MR fluids is a kind of special material, which changes from liquid to solid with the increase of the magnetic field. Using this characteristic, combined with the structure design of the master manipulator, the haptic force can be transferred to the doctor's hand. So, the doctor's tactile presence can be enhanced, and the safety can be guaranteed.

B. The Slave Manipulator

The slave manipulator of the system is shown in Fig.3, it was developed to replace the doctor to complete the operation at the slave side. Corresponding to the master manipulator, the slave manipulator also has two manipulation units, one for the manipulation of a guidewire, the other for the manipulation of a catheter. The insertion, retraction and rotation of the catheter or the guidewire are completed by the stepping motor (ASM4 6AA, ORIENTAL MOTOR, Japan) with a resolution of 0.36 degrees. So, the slave manipulator has four DOFs (Degrees of freedom), and it can complete the collaborative operating of a guidewire and a catheter. In addition, the force information of the guidewire and the catheter can be detected by the load cell (TU-UJ5N, TEAC, Japan) and the torque sensor. The principle of force detection of slave manipulator is shown in Fig.4. Fig.4 (a) shows the method of axial force detection, a guide rail with the sliding block is placed at the bottom of the grasper device to achieve the force transmission. Fig.4 (b) shows the method of torque force detection, the stepping motor, torque sensor and load are connected by the coupling. And the torque force can be transmitted through the synchronous belt (see Fig.3).

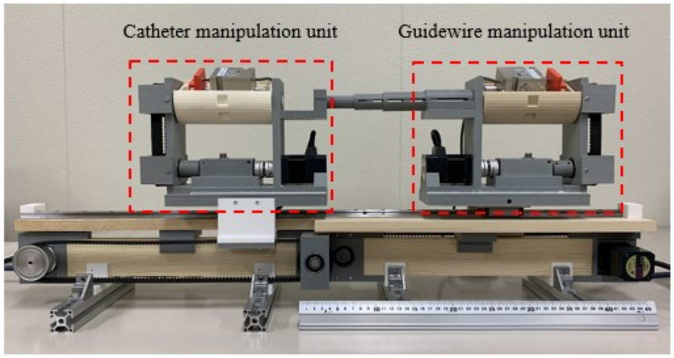
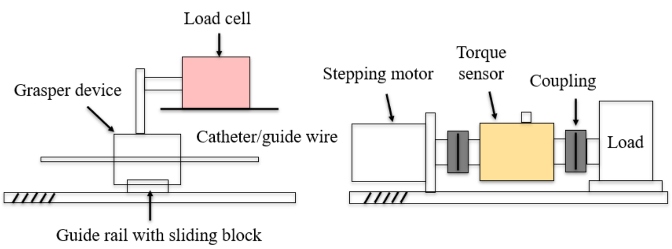


Fig. 3 The slave manipulator of the robot-assisted system.



(a) Axial force detection (b) Torque force detection

Fig. 4 The force detection method of the guidewire or the catheter on the slave manipulator during the operation.

III. Principles and Methods

In this section, a magnetic field generator is used to apply a uniform magnetic field to the tip of the catheter, achieve the deflection of the tip of the catheter and reduce the contact force between the tip of the catheter and the blood vessel wall.

A. *The Magnetic Field Generator*

Fig.5 is the structure of the magnetic field generator, it was designed based on the principle of electromagnetism [31]. And there are two copper coils with an inner diameter of 30 mm, an outer diameter of 120 mm, a height of 68 mm and the turns of 1200 T. To increase the magnetic field intensity, the iron cores are used to pass through the copper coils, the distance between the two copper coils is 30 mm. Besides, after a power supply is connected to the magnetic field generator, a uniform magnetic field is generated. And under the action of a uniform magnetic field, the magnet will be subjected to the electromagnetic force along the N-pole to the S-pole.

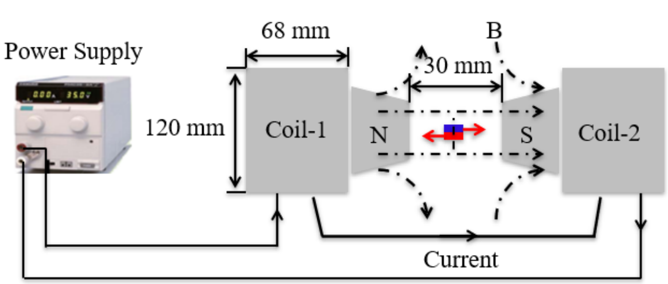


Fig. 5 The structure of the magnetic field generator.

The relationship between the magnetic field intensity and the input current is shown in Fig.6. It is not difficult to find that in the range of 0 A to 2 A, the magnetic field intensity linearly increases with the increase of the input current when the input current is gradually increased in steps of 0.2 A. When the input current is 2 A, the magnetic field intensity is 134.3 mT.

B. *The Deflection of the Catheter Tip*

In some special environments, the blood vessels are more curved, and it is difficult for the catheter to pass through, even with the guidance of the guidewire. Therefore, the advantage of the deflection of the tip of the catheter is to reduce the contact force of the tip of the catheter, and assist the tip of the catheter in passing through the more curved blood vessel environments easily and smoothly.

Based on the principle of the electromagnetic force, a tiny ring shape magnet is installed on the tip of the catheter in this paper. The method for the schematic diagram of the deflection of catheter tip is shown in Fig.7. As shown in Fig.7 (a), a force sensor and a magnet are installed on the tip of the catheter, the force sensor is employed to detect the collision force between the tip of the catheter and the blood vessel wall, and the magnet is employed to assist the deflection of the tip of the catheter in the more curved blood vessel environment under the action of the uniform magnetic field. And as shown in Fig.7 (b), it is the schematic diagram after a magnetic field is applied. Compared with Fig.7 (a), the tip of the catheter can be deflected along the direction of the magnetic induction line, which makes it easier to select the target blood vessel branches and reduce excessive contact. Besides, the deflection angle of the tip of the catheter is related to the magnitude of the electromagnetic force.

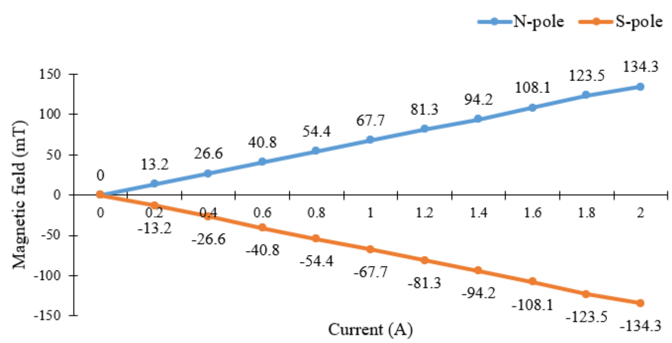
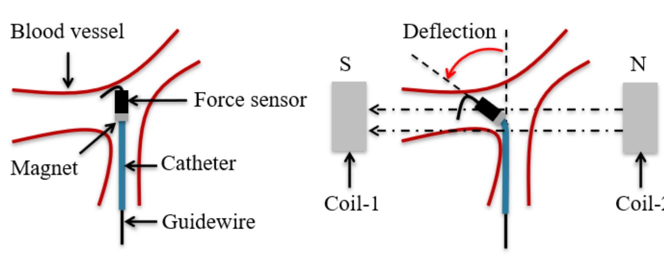
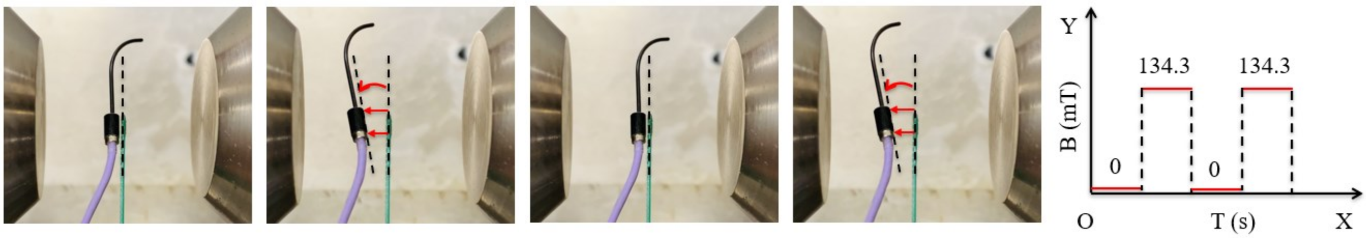


Fig. 6 The relationship between magnetic field intensity and input current.



(a) IAMF (b) IPMF

Fig. 7 The principle of the deflection of the tip pf the catheter (**IAMF**: In the absence of magnetic fields. **IPMF**: In the presence of magnetic fields).



(a) IAMF (b) IPMF (c) IAMF (d) IPMF (e) The change of magnetic fields

Fig. 8 The test results after the test were repeated twice. (**IAMF**: In the absence of magnetic fields. **IPMF**: In the presence of magnetic fields).

C. *The Experiment for the Test*

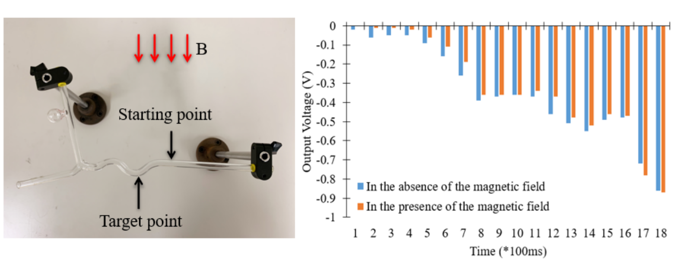
The test results are shown in Fig.8. It was performed at a magnetic field of 134.3 mT. In the initial state (see Fig.8 (a)), a catheter with a magnet was placed in the center of the two iron cores of the magnetic field generator. After a uniform magnetic field was applied to the tip of the catheter, the catheter tip was significantly deflected (see Fig.8 (b)). Then, the magnetic field was turned off, the tip of the catheter was returned to its initial position (see Fig.8 (c)). Finally, the magnetic field was applied to the tip of the catheter again, and the tip of the catheter was significantly deflected again (see Fig.8 (d)). The experiment for the test was repeated twice, the change of magnetic fields with time is shown in Fig.8 (e). And the results are indicated that the proposed method is reasonable and effective.

IV. Experiments and Results

In this section, a comparative experiment is carried out to verify the contact force between the tip of the catheter and the blood vessel wall in the presence and absence of the magnetic field. And the experimental results are obtained, analyzed, and discussed in detailed.

A. *Experimental Setup*

Fig.9 (a) is the comparative experiment was performed in a blood vessel model with the outer diameter of 7 mm and the inner diameter of 5 mm. The starting point, the target point and the direction of the magnetic field were marked. The evaluation index of this experiment is the contact force on the catheter tip during the operation, and the results were detected by a force sensor installed on the tip of the catheter. The experiment was repeated twice, once in the presence of the magnetic field, and once in the absence of the magnetic field. Besides, the applied magnetic field was a constant magnetic field with the intensity of 134.3 mT.



(a) Experimental setup (b) Experimental results

Fig. 9 The evaluation of the contact force between the tip of the catheter and the blood vessel wall during the operation.

B. *Experimental Result*

Fig.9 (b) is the results of the contact force between the tip of the catheter and the blood vessel during the experiment. The results obtained in the absence of magnetic fields is represented by the bars on the left, and the results obtained in the presence of magnetic fields is represented by the bars on the right. It not difficult to find that before 1600 ms, the results obtained in the absence of magnetic fields are higher than the results obtained in the presence of magnetic fields, indicating that the magnetic field reduces the contact between the catheter tip and the vessel wall. But, after the time of 1600 ms, the results obtained in the absence of magnetic fields are lower than the results obtained in the presence of magnetic fields, we believe that the reason is that when the catheter tip reaches the target point, the catheter tip needs to be deflected in the opposite direction of magnetic fields, but the change of the direction of the magnetic field has not yet been realized. The challenge can be solved by changing the direction of the magnetic fields through a program control in future research.

C. *Discussion*

To reduce the contact force between the tip of the catheter and the blood vessel wall in the extremely curved blood vessel environment, improve the safety of the operation, and assist the tip of the catheter to easily pass through the extremely curved blood vessel environment, a method of changing the deflection of the tip of the medical flexible catheter based on the magnetic field control was proposed.

To verify the method proposed in the paper, a comparative experiment of the contact force between the tip of the catheter and the blood vessel wall was performed in the presence of the magnetic field and the absence of the magnetic field. And the contact force was detected by a self-developed force sensor on the tip of the catheter. The experimental results indicated that the contact force has been reduced compared with the absence of the magnetic field, and the method proposed in this paper is reasonable and effective. However, after analysis of the results there are also some limitations. For instance, the change of the direction of the magnetic field has not yet been realized, which result in the phenomena at the time of 1700 ms and 1800 ms in Fig.9 (b), and the limitation can be solved through the program control in the future research. In addition, the current designed magnetic field generator is single, not multidimensional, so the deflection of the tip of the catheter in any direction in space has not yet been achieved, and the limitation can be solved through using a multidimensional magnetic field generator in the future research.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, a preliminary concept was presented for the deflection of the tip of the catheter and the reduction method of the contact force between the tip of the catheter and the blood vessel wall in vascular interventional surgery. A magnetic field generator was integrated in the slave side of the robot-assisted system, it can generate a magnetic field to assist the deflection of the tip of the catheter in the extremely curved blood vessel environment. The advantage of the concept in this paper is that it can increase the safety of the system. Besides, a preliminary experiment was carried out to verify the proposed method, and the results indicated that the contact force has been reduced in the extremely curved blood vessel environment compared with the absence of the magnetic fields. Therefore, we can draw the conclusion that the preliminary concept for the reduction of the contact force is reasonable and effective.

In future research, current limitations will be solved, and if possible, the robot-assisted system will be evaluated in "Vivo".

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