A Surgeon's Operating Skills-based Non-interference Operation Detection Method for Novel Vascular Interventional Surgery Robot Systems

Shuxiang Guo, *Senior Member, IEEE*, Yuxin Wang, *Student Member*, *IEEE*, Yan Zhao, Jinxin Cui, *Student Member, IEEE*, Youchun Ma, *Student Member*, *IEEE*, Gengsheng Mao and Shunming Hong

***Abstract*—The vascular interventional surgery (VIS) is the most popular treatment for the cardiovascular and cerebrovascular diseases. Master-slave VIS robot is a promising technology to further improve the operation accuracy and surgical safety of both the patient and surgeon. The surgical outcome of robot assisted VIS highly depends on surgeon's operating skills. However, current VIS robot systems affect the exerting of surgeon's operating skills with different degrees due to the master manipulators with rigid-link structure or low detecting accuracy. To address this issue, a novel vascular interventional surgery robot based on surgeon's operating skills is developed in this paper. A master manipulator is developed to contactlessly measure the surgeon's operating motion. The surgeon operates the catheter with no limit, just as the operating manner in conventional VIS. It is enabled by measuring the catheter's axial motion through tracking the edge of a series of markers with a macro camera, and by measuring the catheter's rotational motion via a high-precise MEMS (Micro-Electro-Mechanic-System) gyroscope. Then, the developed master manipulator is integrated with a slave robot to construct the master-slave VIS robot system. Experimental results show that the detecting accuracy of the developed master manipulator are 0.71° and 0.104mm. Experimental results of surgical tasks implemented in EVE (endovascular evaluator) indicate that the developed robot system is superior to the system using a phantom as the master manipulator according to the metrics including operating time, path length, maximum speed and maximum accelerate.**

***Index Terms*—Vascular interventional surgery robot, surgeons' operating skills, master manipulator, contactless detection.**

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I. Introduction

CARDIOVASCULAR and cerebrovascular diseases have been one of the top ten causes of people's death all over the world. It brings a huge burden on the world health system [1]. Vascular interventional surgery (VIS) is a new and widespread treatment for cardiovascular and cerebrovascular diseases [2-4]. The surgeon, under the guidance of X-ray image, operates the catheter along vascular to reach the target area [5-6]. Then the surgeon implements certain operations including stent implantation, thrombolysis, balloon embolization of aneurysm and so on. Compared with traditional craniotomy, VIS has demonstrated its excellent surgical outcome, such as reducing the surgical risk and recovery period, alleviating the pain of the patient, reducing the postoperative complications, and so on [7]. However, VIS still has its shortages as follows:

1) The surgeon must be exposed to X-ray radiation during the long operating procedure [8]. It will cause irreversible damage to the surgeon;
2) VIS is a typical subtle and high-risk surgery. The surgeon needs to operate the catheter in a narrow space inside the complex vascular. Minor operation mistakes will lead to serious damages to the patient.
3) Hands tremor, low operation accuracy and misoperation of the human surgeon will further increase the surgical risk in VIS.

Compared with fully-manual VIS, master-slave robot assisted VIS is considered as a promising way to further improving such surgery. First, during robot assisted VIS, the surgeon, outside the operating room, can remotely control the slave robot to implement the surgery [9, 10]. In this way, X-ray radiation received by the surgeon is significantly reduced. Second, the operating accuracy can be improved via precise mechanism and control algorithms. Third, the surgical risk can be further reduced with more sensing information acquired through the robotic system. Our laboratory successfully implemented a clinical trial operation, as shown in Fig.1 [11]. The surgeon can operate the master operator in a safe room, which can isolate X-rays. The slave robot have high operational accuracy compared to manual operation of surgeons. And the surgeon can sense the operation information in the slave side based on force feedback and visual feedback. So, VIS robotic technology has recently become a research focus. But, current VIS robots still have a main limitation on fully exerting the surgeon's operating skills.

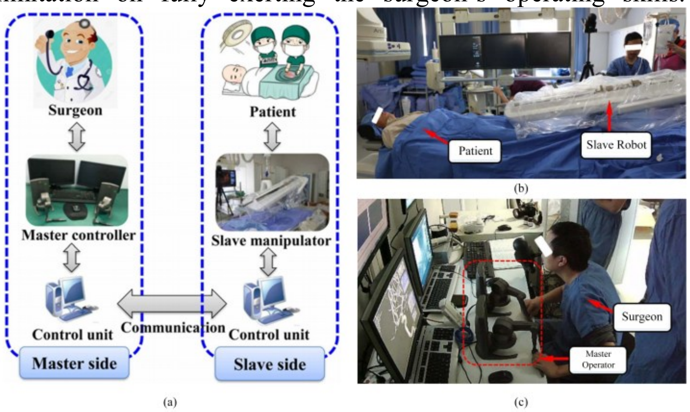

Fig. 1. Clinical trial surgery (a) The structure of the master-slave robot (b) The slave side of the surgery (c) The master side of the surgery. [11]

Surgeon's operating skills are very pivotal and important for the VIS. Guangzhong Yang *et al* [12]developed a method to identify the operating skills of expert surgeons and novice surgeons according to the operating speed, acceleration, force and torque using support vector machine. Evangelos B. Mazomenos *et al* [13] assessed surgeon's operating skills through analyzing the motion pattern of the catheter. Jeremy D. Brown *et al* [14] rated surgeon skill with contact force and robot arm at peg transfer. There are some researchers used the surface electromyography and motion detect for the assessment of the surgeon's operating skills [15, 16]. A novel data glove was used to collect the gesture of the surgeon's hand and skills extracted from gesture was used to train the surgeon in the neurosurgical education [17, 18]. In general, the results all indicate that the expert surgeons with higher-level operating skills have smoother operation, shorter operation time, lower operating force and torque. It means that the expert surgeons have better operating outcome, and the operating skills play a determinant role in VIS for surgical quality and safety.

Therefore, one of the most critical design principles for VIS robot system is to exert surgeon's operating skills as high fidelity as possible during robot assisted VIS. The existing researches on VIS robot systems mainly focus on motion actuate mechanism and perception of the catheter by the slave robot, operating action detection and force feedback by the master manipulator, controllable active catheter and so on. The strain gauges or load sensors are used to detect the torque of the catheter at the slave side [2, 19, 20]. Fiber optic sensor is used to detect the contact force between the catheter tip and vascular wall [21, 22]. The active catheter can push, rotate and change the bending angle, which can increase the flexibility of the surgery [23, 24]. Moreover, some researchers use MR(Magneto-rheological) fluid or ER (Electro-rheological) fluid as the force feedback medium, and the force feedback to the surgeon is controlled by the magnetic field strength or the electric field strength [25-29]. And some researchers use voice coil motor [30] or Phantom desktop haptic device as the force feedback device [31]. Also, some researchers study on the virtual-reality training system for the inexperienced trainee to improve their operating skills [32-35]. Some researches focus on the Control algorithm to improve control accuracy [36]. Although there are so many studies on interventional surgery robots, there are still deficiencies in the study of the master manipulator.

During robot assisted VIS, the surgeon directly operates the master manipulator and uses it to control the slave manipulator. A handy master manipulator is the basis for the master-slave VIS system to exert the operating skills of the surgeon. And the precision and sensitivity of the master manipulator are the prerequisite for accuracy of master-slave system. A master manipulator that can exert the surgeon's operating skills more precisely is significant for surgical safety and quality.

But the master manipulators of the existing VIS robots have limitations on the exerting of surgeon's operating skills. The Phantom desktop haptic device has six degrees of freedom, but operating mode of it and the surgeon's long-term operation methods are completely different, which will affect the exerting of the operating skills that surgeon has developed for a long time. It is not conducive to the surgeon's operation. So some researches try to use a clinical catheter as the operating handle. There are some researches using encoder to detect the motion of the catheter. A series of rollers are applied to two sides of the catheter, and the rollers rotate following the moving catheter drove by the friction force. Then the angle displacement of the roller is detected by the encoder fixed with the shaft of the roller, which represents the movement of the catheter [37-39]. But the way of using encoder has some disadvantages. It will produce a large error, when the catheter and the roller slide relative to each other. Moreover, to reduce the sliding, large positive force would be applied to enlarge the friction force between the rollers and the catheter, which will make the catheter bend. The friction force, as well as the rollers' inertia, will seriously affect the exerting of surgeon's operating skills. Several contactless detection methods are proposed to measure the catheter's movement using a clinical catheter as the operating handle. Detecting the axial and angle displacement of the catheter by measuring the surface texture of the catheter with a laser sensor can reduce the discomfort of the surgeon, but the average measurement error is 0.39 mm and 3° [25, 32]. By detecting the mark on the catheter to calculate the axial and angle displacement of the catheter, the average measurement error are 0.24mm and 2° [40], which are too large comparing with the robot used for the clinical surgery [11]. Also, its theoretical detection range in axial direction was limited to 150mm. This limitation prohibits the application of this method, because the commonly used clinical catheter is about 1.2×10^3mm-1.5×10^3mm length. It indicates that an axial-distance measuring range of 1.5×10^3mm is needed for clinical application.

To fully exert the operating skills of the surgeon with the assistant of VIS robot, a novel robotic system is developed in this paper, called surgeon's operating skills-based VIS robot. A master manipulator is designed to contactlessly measure the movement of the catheter during robot assisted VIS, which do not change surgeon's the original operating habits. A macro camera is used to detect the axial displacement of the catheter, and a MEMS (Micro-Electro-Mechanic-System) gyroscope is used to detect the angle displacement of the catheter. By integrating the master manipulator with a developed slave robot, a novel VIS robotic system is constructed. Experiments are conducted to evaluate the detection accuracy of the developed master manipulator and the performance of the VIS robotic system for surgical tasks implementation in EVE.

II. Methodology

A. The developed master manipulator with contactless detection

The main function of the VIS robotic system is to exert surgeon's operating skills via master-slave control structure in certain surgical tasks. As shown in Fig.2, the surgeon makes decision of operating actions according to the vision feedback (DSA image). The master manipulator is designed to accurately detect the surgeon's operation actions and then sends the action signal in real time to the slave computer via the master computer. The slave computer calculates the control commands for the motors of the slave robot according to the received action signal and the position feedback of the slave robot. The slave robot then implements surgeon's operation actions and operates the catheter to deliver the catheter tip towards the target point along patient's vascular.

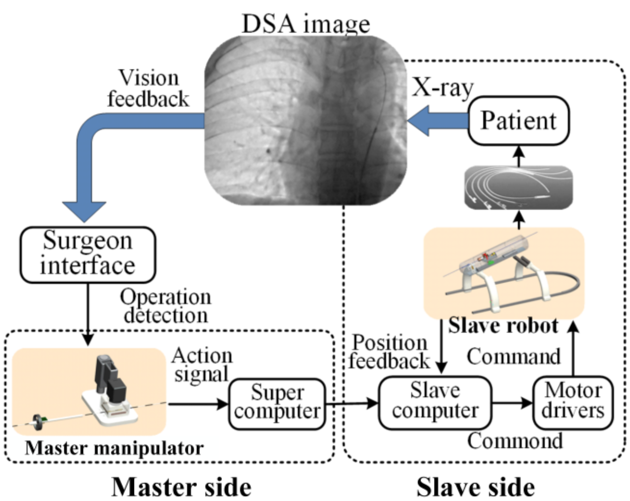

Fig. 2. Schematic diagram of the master-slave VIS robotic system.

During the procedure of robot assisted VIS, the main function of the master manipulator is to detect the surgeon's operation action along axial direction and rotational direction. During conventional VIS, the surgeon generally holds the catheter via a medical twister and operates the catheter by pushing, pulling and rotating action, as shown in Fig.3(a). Although link mechanism has high detection accuracy, the master manipulators using rigid link structure, such as Phantom desktop haptic device, will interfere the exerting of surgeon's operating skills, as shown in Fig. 3(b). During operation, the surgeon operating the handle of Phantom desktop haptic device will feel the constraint of the complex connecting rod and the fixed base. It is different with the operating mode in conventional VIS, as shown in Fig.3(a). Meanwhile, current contactless detection methods, such as laser based methods and marker based methods, cannot meet the demand for VIS due to their limitations of low detection accuracy and small measuring range.

So, a contactless detection method with high detection accuracy and large measuring range is important for the master-slave VIS robotic system. Inspired by the medical twister used in conventional VIS, a novel master manipulator is developed to eliminate the effect of the master manipulator on the surgeon's hand and then fully exerts the surgeon's operation skills. This master manipulator allows the surgeon to operate the medical catheter and do not change the operating habits of the surgeon.

Fig. 3. (a) The medical twister that surgeon used in the VIS (b) Phantom desktop haptic device used in existing VIS robot.

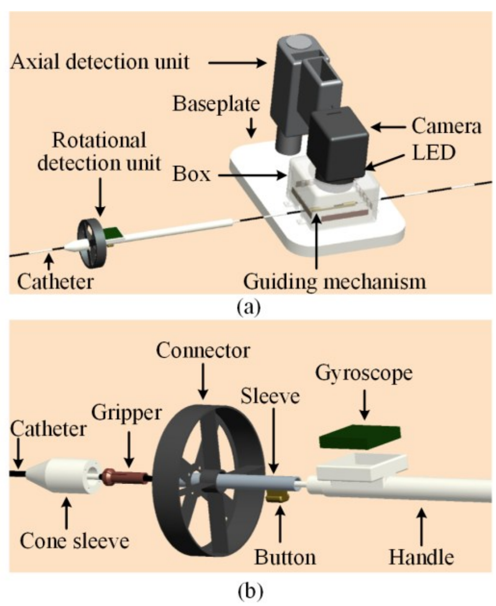

Fig. 4. Structure of the developed master manipulator (a) Top view of the master manipulator (b) Exploded view of the master manipulator.

As shown in Fig.4 (a), the developed master manipulator mainly consists of two units: axial detection unit based on a macro camera and rotational detection unit based on MEMS gyroscope. The axial detection unit is fixed onto a baseplate. The catheter is designed with a series of black markers. A macro camera is used to acquire the image of the moving catheter, with which the axial moving information could be computed by tracking the mark edge. A box equipped with a set of LEDs (Light Emitting Diode) is employed

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to provide a stable illumination condition for the camera. A guiding mechanism is designed to remain the catheter parallel to the axis of the camera view.

The detailed structure of the rotational detection unit is shown in Fig.4(b). The rotational displacement is acquired by a MEMS gyroscope, which is assembled with a designed handle. One of the axis of the gyroscope is parallel to the axis of the handle. To achieve large axial and rotational measuring range, the handle is designed to realize rapid clamping and loosening of the catheter. The handle consists of a sleeve fixed with a button, a connector, a gripper, and a cone sleeve. The connector links the handle with the cone sleeve (The connector is also used to detect the operating force of catheter in our further research work). The gripper is coaxial with the sleeve, the handle, and the cone sleeve. The front end of the gripper is designed with a conical surface, and the inner of the cone sleeve's front end is also designed with a conical surface. When the surgeon pushes the button forward, the sleeve presses the gripper. The pressure between the conical surfaces of the gripper and the cone sleeve leads to elastic deformation of the gripper, and the catheter can be clamped by the gripper. Then push the button along the rotational direction into a groove to lock the button. When the surgeon pulls the button backward, the catheter can be loosened. By alternatively clamping, loosening, rotating, pushing and pulling the catheter via the handle, the catheter can be operated without limitation on axial and rotational moving displacement. When the catheter is pushed or pulled, the axial detection unit can detect the axial displacement of it. When the catheter is rotated, the MEMS gyroscope can detect the angle displacement of it.

In this way, the axial and rotational displacement of the catheter can be detected by the developed master manipulator. The detailed mathematical model of the developed detection method will be illustrated in the next section.

B. Axial displacement detection method

To precisely detect the motion of catheter's axial displacement without disturbing the operating skills of the surgeon, we developed a contactless method based on the digital image processing. First, make spaced marks on the catheter and the width of the marker is about one-half the width of the camera view. Second, pass the catheter horizontally through the camera view via a guiding mechanism. Then, the axial displacement of the catheter is detected via a macro camera with fast edge detection algorithm. Divide the detection area of the camera view with a certain margin X on the left sides. When the detection of the mark edge is updated between two frames, as shown in Fig. 5, the detected mark edge at time T_{t-1} is defined as Div1, and the detected mark edge changes into Div2 at time T_t. The previous mark edge Div1 is defined as Div1'. The detected mark edge changes into Div3 at time T_{t+1}. If there is no margin X, the detected mark edge moves to the edge of the camera view in current frame, and the catheter continues to move. The detected mark edge will disappear from the camera view in next frame. It will result in detection failure. By setting the margin X, the detected mark edge will change to the other mark edge in the middle area of the camera view, thus realizing continuous detection. The position of the mark edge is detected by comparing the gray value of adjacent pixels from left to right of the camera view.

The maximum speed of the surgeon's operation in the VIS is 365.3 mm/s. The maximum detection speed of the developed master manipulator is set to 750 mm/s, and the image acquisition speed of the camera (Baumer, VLU-02M,pixel size of 640×480) is 160 frames per second. The equation between X and the maximum detection speed is

$$\mathrm{X} * \alpha * \mathrm{f} \geq V_{\max} \tag{1}$$

where α is the actual distance in world coordinate system represented by each pixel in the camera view; f is the image acquisition speed of the camera and V_{max} is the maximum detection speed, which is set to 750 mm/s. The camera field width is about 20mm, so the X is set to be 150 pixels. The length of each mark is about 320 pixels in the camera. According to the maximum speed of the catheter that is 365.3mm/s, the catheter won't move more than 75 pixels between adjacent frames in the camera view, which is one quarter of the length of the catheter.

The catheter moves through the detecting area in the camera view. When the detection of the mark edge is updated between two frames, as shown in Fig. 5, the detected mark edge at time T_{t-1} is defined as Div1, and the detected mark edge changes into Div2 at time T_t. They are different edges on the catheter, the discrepancy of Div1 and Div2 is large than the pre-set threshold value X, and the speed won't be large than the maximum detection speed. So the fast edge detection algorithm will search the other mark edge Div1' in the full field of camera view at time T_t. The axial displacement of the catheter from T_{t-1} to T_t can be given as

$$P2 = Div1' - Div1 \tag{2}$$

Then, the mark edge continues to move through the detecting area, as shown in Fig. 5. The detected mark edge at time T_t is defined as Div2. Then the next frame at time T_{t+1} is acquired. The detected mark edge at time T_{t+1} is defined as Div3. The axial displacement of the catheter from T_t to T_{t+1} can be given as

$$P2 = Div3 - Div2 \tag{3}$$

And the reverse movement of the catheter is also a similar principle.

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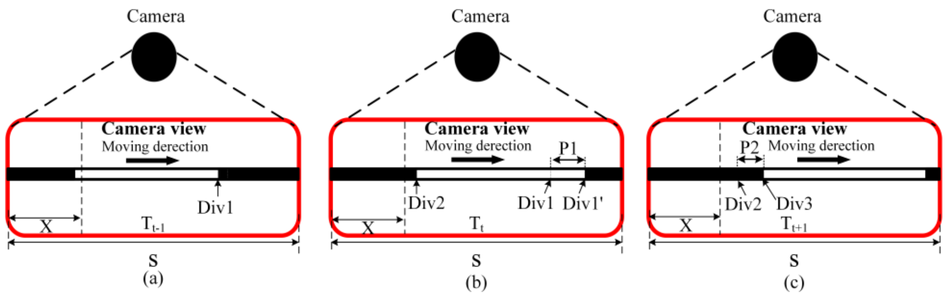

Fig. 5. The mark edge moves in the camera view (a) Camera view at time T_{t-1} (b) Camera view at time T_t (c) Camera view at time T_{t+1}.

C. Angle displacement detection method

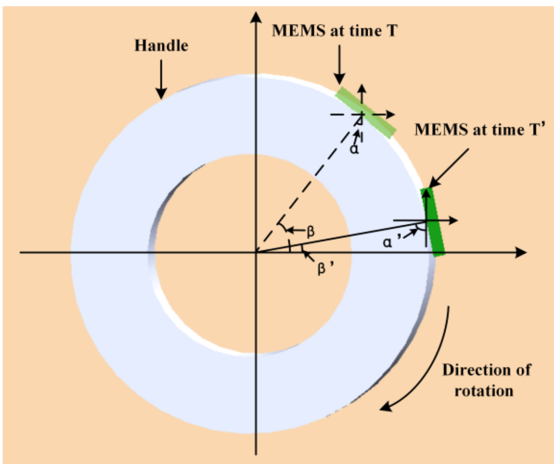

Fig. 6. Rotation angle detection principle.

Because of the limited diameter of the catheter, detecting the rotation angle of the catheter by means of laser and marker will cause a large error. And the detection accuracy will decrease as the diameter of catheter decreases, which is inappropriate in practical applications. The diameter of the catheter is relatively small. The surgeon usually uses a medical twister to operate the catheter. Inspired by the medical twister, this paper puts forward a novel method to detect the rotational movement of the catheter, in which a MEMS gyroscope is assembled on the handle in parallel of the axis of the handle. When the surgeon rotates the catheter via the handle, the MEMS gyroscope rotates around the axis of handle.

There are two oppositely placed capacitor plates inside the gyroscope. When the gyroscope accelerates, the plates move under the influence of Coriolis force, which will cause change of the voltage on the plate. According to the change value of the voltage on the capacitance, the displacement of the plates can be obtained. The Coriolis force is relative to the plate motion displacement and the Coriolis force is relative to the angular velocity.

$$F_c = 2m\omega \times V \tag{4}$$

Where F_c is the Coriolis force; m is the mass of the moving object; V is the vector velocity of the moving object; ω is the vector angular velocity of the rotating system, and × represents the cross product of the two vectors.

So the angular velocity of the MEMS gyroscope can be obtained according to the voltage on the capacitance. The angle displacement of the MEMS gyroscope can be calculated by integrating the angular velocity. And there will be some drift cause by the noise in the gyroscope's signal, most of which are high frequency signals. A low pass filter with low/high cut off frequency 0/50HZ is used to filter out the noise in the gyroscope's acceleration signal [41-42].

Considering that the MEMS gyroscope is not coaxial with the catheter and the handle, it is necessary to prove that the angle displacement detected by the gyroscope is equal to the rotation angle displacement of the catheter. When the handle is rotating, the MEMS gyroscope rotates with the handle. As shown in Fig. 6, the angels of the handle and the MEMS gyroscope at time T are respectively defined as β and α. The angels of the handle and the MEMS gyroscope at time T' are respectively defined as β' and α'. The relationships between α, α', β and β' can be obtained according to geometric principle:

$$\alpha + \beta = 90^\circ \tag{5}$$

$$\alpha' + \beta' = 90^\circ \tag{6}$$

Subtracting the above two formulas:

$$\alpha' - \alpha = \beta' - \beta \tag{7}$$

So the rotational angle displacement of the handle is $\beta' - \beta$, which is equal to the rotational angle displacement of the MEMS gyroscope $\alpha' - \alpha$.

D. Structure of the slave robot

The structure of the slave robot is shown in Fig.7. The slave manipulator is designed to mainly realize axial and rotational movements of the catheter. The whole slave manipulator is assembled onto a pair of supporting arms. The supporting arms are linked with a T-style guider. The T-style guider is a standard connector of clinical operating table. A liner actuator is assembled between the supporting arm and the slave manipulator. The supporting arm and the linear actuator have the ability to adjust the slave manipulator position and posture with 3 DOF (degree of freedom). The detailed structure of the slave manipulator is shown in Fig. 7(b). The motor (SGMJV-01ADE6S with controller SGDV-R90A01B) and a ball screw fixed with the baseplate are used to generate linear motion of the components assembled on its sliding block. It consists mainly of the servo motor (EC-max16 with manipulator Maxon

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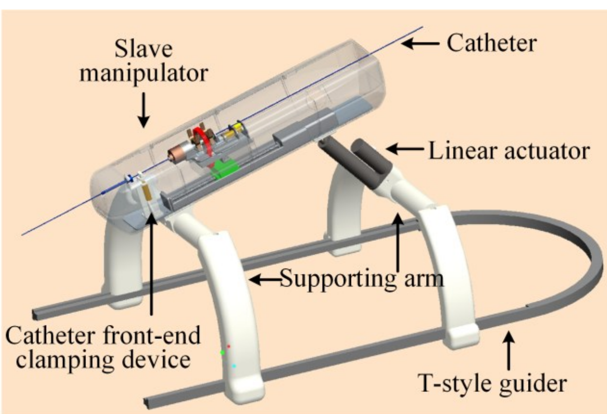
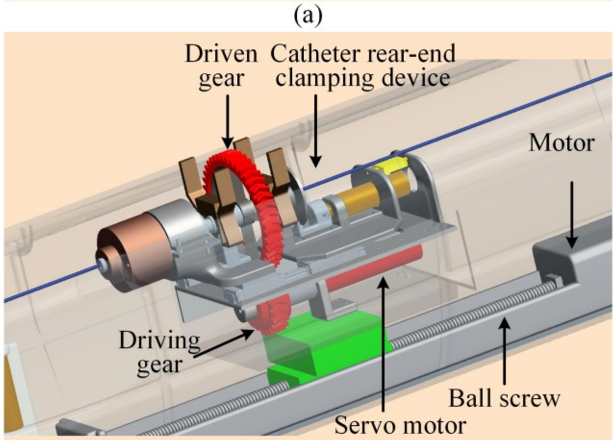
epos2 50/2, reduction ratio 84:1), a pair of herringbone gears, and a designed catheter rear-end clamping device. The catheter rear-end clamping device is used to clamp the catheter. The herringbone gears are driven by the servo motor. The driven gear is fixed with the catheter rear-end clamping device. Therefore, when the driven gear is rotating, the catheter will be rotated together. In this way, the axial motion and rotational motion of the catheter can be realized by the slave robot.

It should be pointed out that, the ball screw has the limitation of distance of travel. So, a catheter front-end clamping device is designed and fixed with the baseplate. When the end point of the distance of travel is arrived, the catheter front-end clamping device clamps the catheter, and the catheter rear-end clamping device loosens the catheter. Then the slave manipulator is driven backward by the stepping motor to the starting point of the travel distance of the ball screw. Then the catheter front-end clamping device loosens the catheter, and catheter rear-end clamping device clamps the catheter. Then the slave manipulator starts again to conduct push, pull and rotation action on the catheter. In this cycle, the axial and rotational movement of the catheter can be continuously realized until the catheter tip reaches the target point for the given surgical task.



(a)



(b)

Fig. 7. Structure of the developed slave robot (a) Overall structure (b) Detailed structure of the slave manipulator.

III. Evaluating Experiments

In this section, the developed master manipulator is firstly calibrated via experiments. Then further experiments are conducted to evaluate the performance of the developed master manipulator and the master-slave robotic system.

A. Experimental setup

The experimental setup is shown in Fig.8. The whole setup is fixed on a test-bed. Motor A is linked with the handle of the master manipulator to rotate it with certain angle speeds. Motor A is also fixed with the sliding block of a ball screw. The ball screw is driven by a motor B to push or pull the handle with certain speeds. The axial detection unit of master manipulator detects the axial displacement of the catheter. A laser sensor (Keyence IL-100 laser ranging Instrument with Keyence IL-1000 amplifier, repeat detection accuracy of 4μm) is used to detect the axial displacement of the handle. The laser sensor detects the distance between the reflector and the laser sensor, which is used as the real data for the catheter's axial displacement. This distance detection method of the laser sensor using the triangulation method has high precision. The triangulation method is different from the way developed by Guo [25], in which they use the laser sensor to detect the texture of the catheter. The encoder (HK38-D8G5-30FL2500PL6T1, 2500 count-per-revolution quadrature encoder) is used to detect the angle displacement of the catheter, which is used as the real data. By detecting the two phases output pulse signal of the encoder, we divide each circle by 10000 equal parts according to the phase difference, so the detection resolution of the encoder is 0.036 degrees.

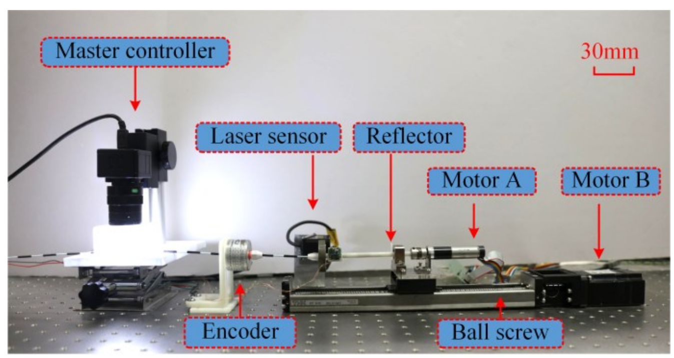


Fig. 8. Experimental setup.

B. Calibration of the developed master manipulator

By comparing the displacement detected by the laser sensor and the macro camera, the actual distance represented by each pixel is obtained. Thereby the calibrating equation of the line detecting device is

$$\alpha = \frac{S}{n} \tag{8}$$

where α is the actual distance in world coordinate system represented by each pixel in the camera view; S is the actual distance in world coordinate system detected by the laser sensor, and n is the number of pixels that the mark edge moves in the camera view.

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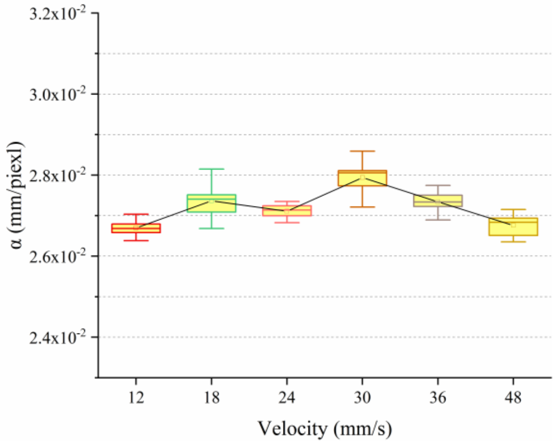


Fig. 9. Linear detection calibration.

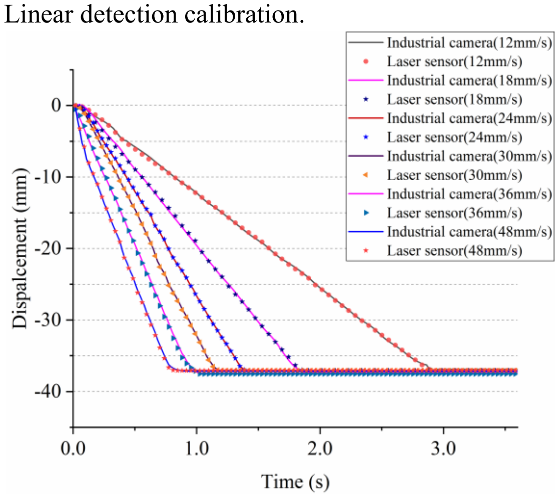


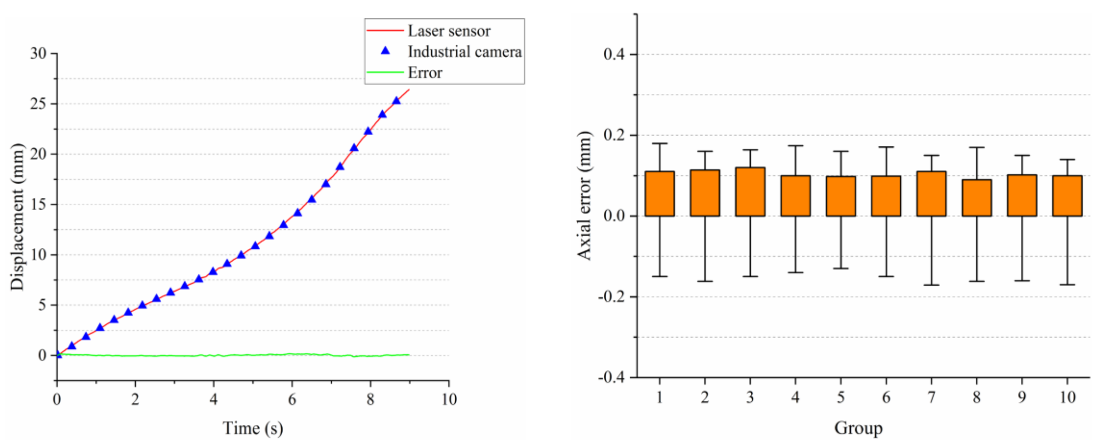
Fig. 10. Different alignment curves at a constant speed.

Calibration experiments under 6 different speeds (12 mm/s, 18 mm/s, 24 mm/s, 30 mm/s/, 36 mm/s and 48 mm/s) are conducted. As shown in Fig.9, the average value of α under different speeds ranges from 0.0268mm/pixel to 0.0281mm/pixel. The deviation area of α under different speeds ranges from 0.0005mm/pixel to 0.0014mm/pixel. The final value of α is 0.0273mm/pixel. Then we can get the value of the axial displacement measured by the developed master manipulator and compare it with the axial displacement detected by the laser sensor, as shown in Fig.10. The mean error of the axial displacement under different speeds is 0.098mm, and the max error is 0.170m.

C. *Calibration of the developed master manipulator*

Experiments are conducted to evaluate the detecting performance of the developed master manipulator using the experimental setup shown in Fig.8. When motor A drives the handle to rotate with certain speeds, the gyroscope detects the angle displacement of the handle. At the same time, an encoder fixed with the catheter via a griper is used to detect the real angle displacement of the catheter. Then the catheter is loosened by the gripper and motor B drives the handle moving along axial direction. The axial detection unit of the master manipulator detects the axial moving displacement of the catheter and the laser sensor detects the axial displacement of the operating handle. The angle displacement and axial displacement detected by the encoder and the laser sensor are used as the real value to analyze the detection error of the master manipulator.

As shown in Fig. 11, the catheter moves under variable speed to simulate the hand movement of the surgeon during VIS. We repeat the experiments for 10 times. The catheter detection performance is shown in the Fig.11. The average error of the axial detection error is 0.104mm, and the maximum axial detection error is below 0.180mm.The angle displacement detection performance of the developed master manipulator is shown in Fig.12. The average error of angle displacement by comparing the master manipulator with rotary encoder is 0.71°, and maximum error is 1.87°.



(a) (b)

Fig. 11. The performance of the axial displacement detection (a) The performance of the developed master manipulator in one experiment (b) The statistical results of the developed master manipulator.

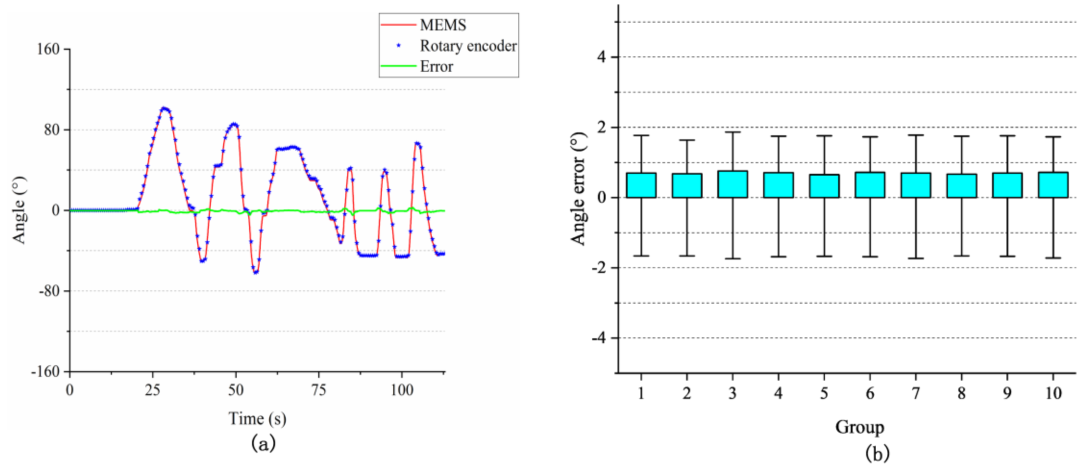


Fig. 12. The performance of the angle displacement detection (a) The performance of the developed master manipulator in one experiment (b) The statistical results of the developed master manipulator.

D. Evaluation of surgical task implementing performance

To evaluate the performance of the developed master-slave robot for implementing certain surgical task of catheter delivering, the robot system is integrated within an operating room to develop the experimental setup, as shown in Fig.13. The master manipulator is located at the control room, while the slave robot is fitted together with the operating bed via its supporting arm. An EVE (endovascular evaluator) is used to provide the operating environment. It is a human vascular model with the scale of 1:1 compared with a real human patient. The surgical path for the given surgical task is shown in Fig. 13(c-d). The starting point is located inside the aortic arch and the target points are respectively located inside the left subclavian artery and left common carotid artery. The target point of task one is located in the left subclavian artery as shown in Fig 13(c) and the target point of task two is located in the left common carotid artery as shown in Fig 13(d). These two surgical paths are the representative surgical tasks for intracranial angiography. The angiographic system is used to provide the operator with the visual feedback of the surgical state inside the EVE.

According to the angle and axial tracking performance, as shown in Fig. 14, there is a time delay between the salve catheter and the master catheter due to the signal transmission process. The master signal has to be processed by master computer and then sent to the slave computer which will control the movement of the salve motor. And it takes the slave motor some times to move to the command position. The time delay will cause the tracking error between the master manipulator and the slave catheter. The average tracking error of the axial displacement is 0.25mm, and the maximum error is 1.2mm, as shown in Fig. 15(a). The average tracking error of axial displacement is 0.51° and the maximum error is 1.8°, as shown in Fig. 15(b). The tracking error is acceptable for the interventional surgery comparing to the robot-assisted interventional surgery implemented in human [11].

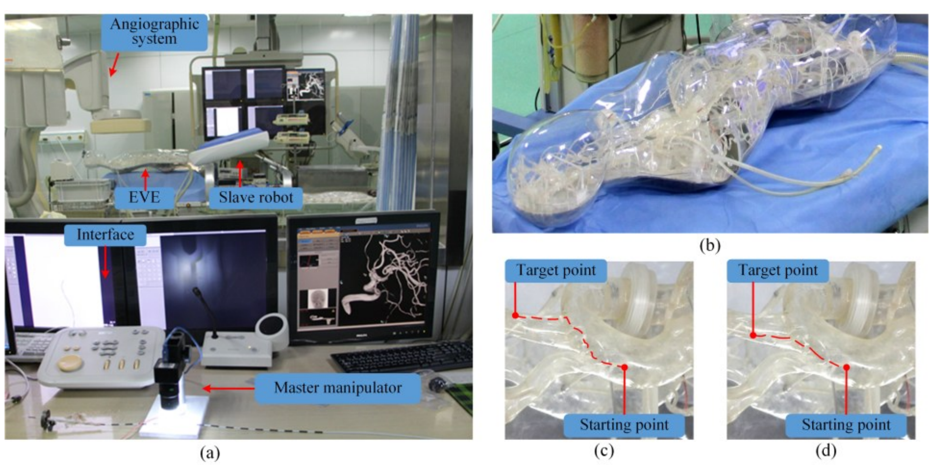


Fig. 13. Experimental setup (a) Detail inner view of the slave robot, (b) EVE in operating room, (c) Surgical task one, (d) Surgical task two.

Experiments are conducted to evaluate the developed master manipulator compared with a Phantom desktop haptic device. For a more intuitive comparison of the two modes of operation, the force feedback function of the phantom desktop haptic device is disabled. There were 10 surgeons involved in the experiment, including 6 novice surgeons (<50 procedures), 4 expert surgeons (> 500 procedures), 4 female surgeons, 6 male surgeons. The age of novice surgeon are between 25-35 years old. The age of expert surgeon are between 45-55 years old. 10 experiments are repeated per surgeon. Analysis method of the final experimental results is single factor analysis. From the operating skill evaluation index introduced by the Yang GZ et al [43], we choose the maximum acceleration, maximum speed, operating time and path length of the catheter as the evaluation index. By comparing the index of the developed master manipulator and Phantom desktop haptic device in the robot-assisted VIS under two surgical tasks, surgeons implement the given surgical tasks via the developed master manipulator with less operating time, shorter path length, smaller maximum speed and smaller maximum acceleration, as shown in Table.1, which means that the developed master manipulator can exert the operating skills better. The phantom desktop haptic device has limitation on the axial displacement and rotary displacement. Surgeons need constantly folding back the joystick of the phantom haptic device to ensure continuous operation, which does not match the operation of the medical catheter. Furthermore, surgeons have been trained to use the catheter and guide wire for years or decades. It is hard for them to give up their original operation procedures and create new operation habits on a new operating tool. Therefore, the designed master controller is better than the phantom desktop haptic device in terms of surgeons' operating procedures. Surgeons can better exert the operation skills when operating the master manipulator, and do not need to adapt to the phantom haptic device. The operation curve is smoother, and errors will be reduced when entering the ascending vessels. In terms of the surgeon's operating habits, the developed master manipulator conforms to the surgeons' original operating habits and the surgeons' operating skills can be better exerted via the developed master manipulator in the robot-assisted VIS.

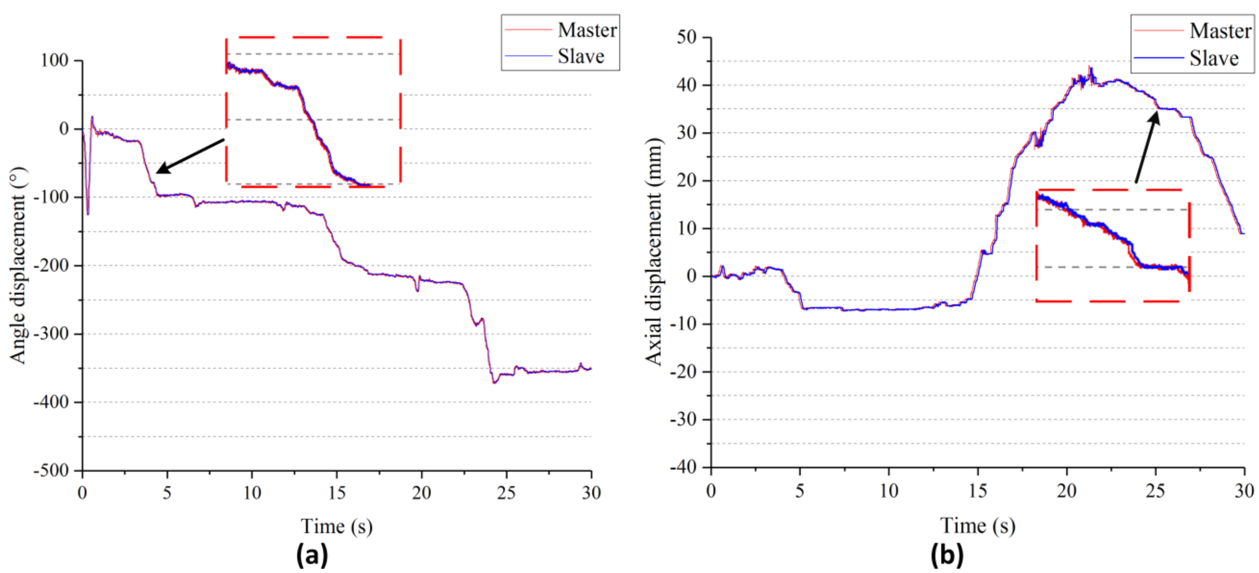


Fig. 14. Tracking performance of developed master manipulator in task one (a) The tracking performance of the angle (b) The tracking performance of the axial displacement.

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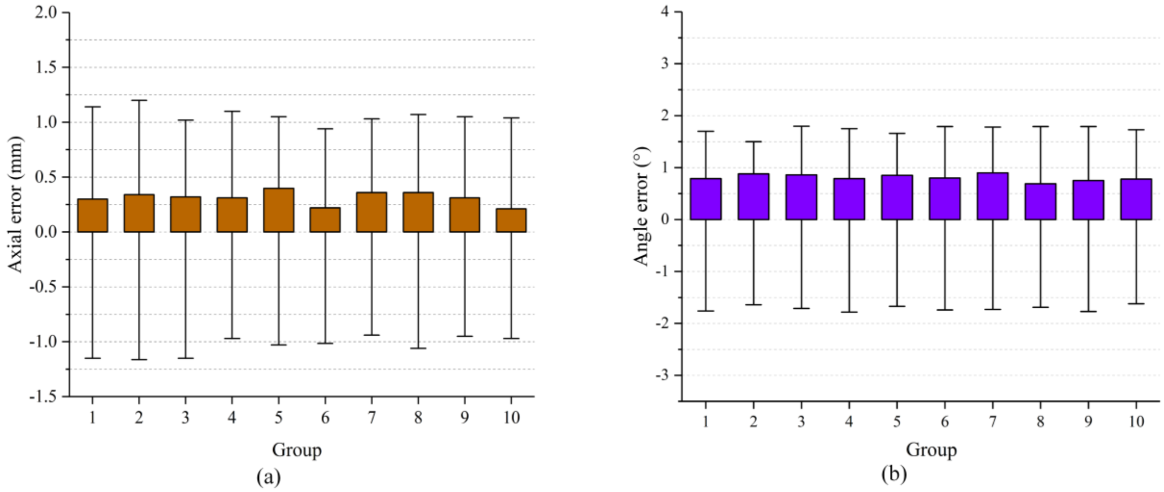

Fig. 15. Statistical results of the master-slave robot (a) Statistical results of the axial tracking error, (b) Statistical results of the angle tracking error.

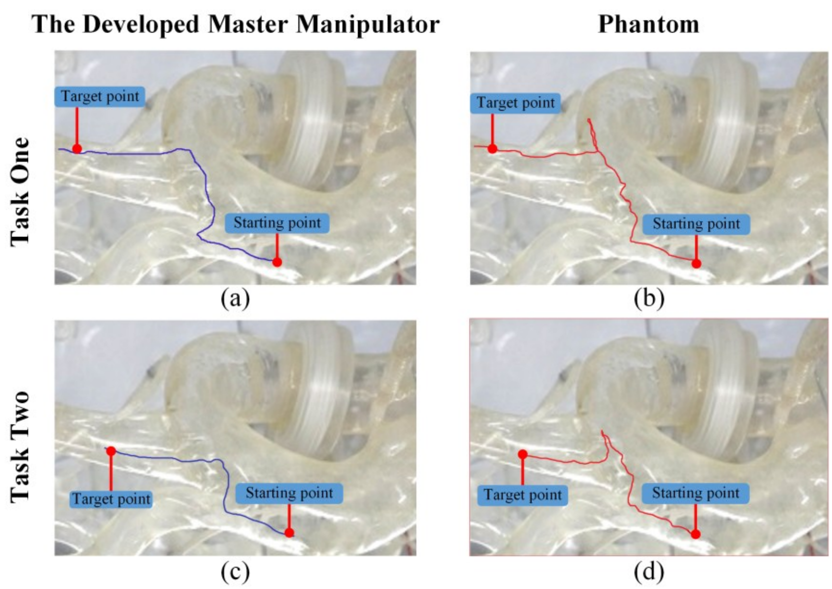

Fig. 16. Comparison results of the operation path between phantom and the developed master manipulator. (a) The operation path under task one using the developed master manipulator (b) The operation path under task one using the phantom (c) The operation path under task two using the developed master manipulator (d) The operation path under task two using the phantom.

TABLE I
COMPARISON OF SURGICAL OPERATION INFORMATION BETWEEN PHANTOM AND THE DEVELOPED MASTER MANIPULATOR

	Task one		Task two	
	Phantom desktop haptic device	The developed master manipulator	Phantom desktop haptic device	The developed master manipulator
Operating time(s)	56.5	33.4	63.3	35.2
Path Length (mm)	136.8	102.3	110.5	89.4
Maximum Speed (mm/s)	343.8	275.3	364.4	226.1
Maximum Acceleration (mm/s^2)	990.6	454.2	1.04×10^3	497.8

IV. Discussion

The surgeon's surgical skills are the determining factors of the surgical outcome and success rate in the surgery. Therefore, it is very important to maintain the surgeon's operating skills during robot assisted VIS. Also in the master-slave robotic system, the accuracy of the master-manipulator is the basis for the whole system. A contactless and high-precision master manipulator is critical for the master-slave robotic system.

The existing master manipulators use Phantom desktop haptic device to detect the surgeon's operation, which are inconsistent with the original surgeon's habit in conventional VIS. It is not conducive for the surgeons to exert the original operating skills. Moreover, the contactless detection device based on the laser sensor [25, 32] has low precision. During the interventional procedure, the surgeon operates a 1.2×10^3mm-1.5×10^3mm catheter, and the mark based contactless catheter sensing method [40] is only 150mm, which can't meet the needs in clinical operation. This paper developed a novel method for detecting the movement of the catheter without interfering the surgeons' operating skills. The axial displacement of the catheter is detected by the macro camera and the angle displacement is detected by the MEMS gyroscope. The developed method can meet the high-precision detection of the catheter movement without affecting the surgeon's operating habits. Moreover, there is no limit on the angle displacement and the length of axial displacement detection, which can satisfy the needs in the clinical surgery. And the accuracy of the detection does not change as the length of the catheter increases. In addition, the developed detection method has no limitation on the diameter of the catheter. It can be used to detect the motion of the guide wire, which has the same accuracy with the catheter. The slave robot can operate both the catheter and guide wire. The VIS robotic system developed in this paper can guarantee the same accuracy for catheter and guide wire. Further, the detection accuracy of the axial displacement can be further improved by using a higher resolution camera. When the number of pixels in the camera view increases, the resolution of the master manipulator can be improved. Also a high frame rate camera with narrower width of camera view can be used to increase the resolution. The angle displacement is obtained through quadratic integral to the acceleration, which is the source of the angle displacement error. Therefore, the performance of the angle displacement detection can be improved by increasing the sampling rate of acceleration.

The experimental results indicate that surgical tasks of VIS can be well implemented through the developed master-slave VIS robotic system. It provides an effective way to protect the surgeon from the harm of X-ray radiation. Also, it provides possibility of further superiority for robot assisted VIS, which has high clinical value, such as eliminating the effect of hand tremor, high-precision operation, security early warning, even semi-autonomous robotic operation and so on. Furthermore, via the master-slave VIS robotic system, the patients in remote mountain areas can get access to optimal treatment from expert surgeons at developed regions, which is beneficial to solve the issue of uneven distribution of medical resource.

V. Conclusion

In this paper， a contactless detection method with high precision is proposed to detect the surgeon ' s axial and rotational operating actions on the catheter in real-time based on macro camera and MEMS gyroscope. A master manipulator prototype is developed based on the developed detection method. Then, a master-slave VIS robot system is constructed by integrating the master manipulator and a developed slave robot. Surgical task implementation performance evaluating experiments of the developed master-slave VIS robotic system in EVE are conducted under the guidance of the angiographic system in an operating room.

1) Since a medical catheter is used as the operating handle, the operating mode is similar to that in traditional VIS. So the surgeon's operating skills can be implemented effectively.
2) The detection accuracy of the developed master manipulator is 0.104mm and 0.71°. Compared with Yin's laser-based method [25, 32], whose detection accuracy is 0.39mm and 3°, the detection accuracy of axial action and rotational action are improved respectively by 73% and 76%. Compared with Jin's marker-based method [40], whose detection accuracy is 0.24mm and 2°, the detection accuracy of axial action and rotational action are increased by 57% and 64%. And, there is no limit on the measuring range of axial action, which can meet the needs of clinical surgery.
3) Basic surgical task of catheter operation in EVE is well implemented through the developed VIS robot system under DSA angiography. The axial and rotational tracking performance between the slave robot and master manipulator satisfy the clinical demands of VIS.

The contactless detection method has no interference force on the catheter. In the future work, the force feedback device will be integrated to the designed master manipulator to make the surgeon feel the most realistic operation experience, maximize the surgeon's operation skills, and increase the safety and efficiency of the master-slave VIS robot.

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