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A Novel Wearable Master Manipulator for the Remote Vascular Interventional Surgery

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Abstract **- Vascular interventional surgery (VIS) mainly relies on the surgeon's clinical experience and the image assistance of digital subtraction angiography (DSA). However, DSA will damage the surgeon's health. A master-slave vascular interventional surgical robotic system averts the threat of the X-ray, whereas most master manipulators of the system still have some problems, such as the different operating modes compared to the convention and the large inertia of the device itself. Therefore, a wearable device with precise measurement function, SurGlove, is developed in this study. The surgeon can wear SurGolve as the common medical glove and handle the catheter and guidewire directly. The film pressure sensor on the glove can judge the grasping signal and enable the optical tracking system to measure the markers on the device. The spatial rotation angle and displacement distance of the SurGolve are calculated in real-time. By wearing SurGlove, the surgeon can manipulate the guidewire and the catheter cooperatively. Furthermore, the evaluation experiments showed that the proposed device had a mean absolute error of 1.88° and a maximum error of less than 3° in rotation angle measurement. The maximum displacement error was less than 5 mm and the mean absolute error was 1.53 mm. This study preliminarily verified the feasibility of the proposed wearable SurGlove for the VIS robotic system.**

Index Terms – Wearable device, vascular interventional surgery robotic system, master manipulator, surgeon's habits, SurGlove.

I. Introduction

Vascular interventional surgery (VIS) has become a superior choice for cardiovascular and cerebrovascular diseases because of its shorter recovery time and minimally invasive [1]. During the operation, surgeons get guidance and assistance from digital subtraction angiography (DSA). But the X-ray from the DSA harms surgeons' health, and 20-kg lead clothing is an indispensable part of protecting surgeons' health. Recently, with the development of robot technology, more robot-assistant vascular interventional systems have been available. These systems overcome the shortage of the conventional VIS, for instance, make the surgeon separate from the X-ray radiation to reduce occupational hazards and compensate for the surgeon's hand tremor to improve the accuracy of stent placement. Most vascular interventional robots employ the master-slave structure. The surgeon operates the master manipulator to control the slave manipulator. A slave manipulator has the ability to handle interventional surgery instruments. At the same time, the contact force is collected by the slave manipulator and sent to the master-side. It will provide the surgeon with haptic force feedback and improve the transparency of the operation [2]-[3]. However, the master-slave structure separated the surgeon and surgical instruments, making surgeons unfamiliar with the operation of the interventional surgical robot, influencing the result of the surgery.

At present, the major commercial VIS robots adopt the key or rotary knob to control the salve manipulator, such as the CorPath® Robot System (Corindus Robotics Inc., Waltham, MA, USA)[4], and Amigo® Robot System (Catheter Precision Inc., Ledgewood, NJ, USA) [5]. Surgeons must be retrained to use this type of master manipulator, as it does not conform to their operating habits. Apart from the commercial VIS robots, there are some experimental VIS robot systems. Above the literature survey, the result shows that most of the master-slave vascular interventional robot comprises a linear stage for acquiring the insertion and a fixed-axis rotary mechanism for rotation acquisition [6]. Yan *et al.* developed a VIS robotic system controlled by a movable joystick[7]. Bao *et al.* use two commercial haptic devices (Geomagic® Touch X,3D Systems, Inc., USA) as the manipulator to handle the guidewires and catheters[8],[9]. Cha *et al.* developed a master manipulator with a telescopic parallel structure, which provides force feedback by a DC motor. But the handle is not the guidewire or catheter, the surgeon needs to learn the handle's operation[10]. Zhou *et al.* developed a surgeon's habits-based novel master manipulator for the VIS Master-Slave Robotic System. However, the operating handle is connected to the motor, which brings about a large rotational inertia that affects the operator's operating experience[11]. Guo *et al.* developed a master manipulator based on magnetorheological fluids and integrated the optical sensor to measure the displacement of the catheter directly. However, the size of the electromagnetic generator (used to produce feedback force) is too large to be practical, and optical sensors are difficult to guarantee the accuracy of the measurement[12][13]. Most of the current research still uses a manipulator to which encoders or sensors are connected to collect information about the displacement and rotation of the operator. This structure introduces greater inertia, requiring the operator to move the measuring unit together when operating the lever. [14] mentioned that the range of haptic force in vascular interventional surgery is about 0.1N to 2N. Therefore, the inherent inertia of the structure will greatly affect the user's haptic perception and complicate the haptic rendering control. Optical positioning is one of the common positioning methods. It has high accuracy and a wide field of view (FoV)[15][16]. Moreover, the optical tracking system is less affected by the environment, so it is widely used in surgical robots[17].

Motivated by the above consideration, this paper mainly focuses on addressing the operational measurement method of low inertia for the master manipulator of the VIS robotic system. An optical tracking system (OTS) is used to obtain the location information of retro-reflective markers mounted on the wearable operating device. The surgeon wears handling gloves and can directly operate the existing guidewire and catheter to control the slave robot.

The specific contributions of this study are as follows:

1) reducing the master manipulator's inherent inertia by implementing a non-contact displacement measurement method with high performance,
2) developing a wearable device to retain the operating habits of surgeons in clinical surgery and not implement joysticks.

This paper is organized as follows: The prototype of the wearable device and the principle of OTS are illustrated in Section II. In Section III, experimental protocol and processing methods are illustrated. Finally, Section IV concludes this article.

II. Material and Method

A. Design and components of the proposed wearable devices

Fig.1 presents the entire design of the novel master manipulator as a wearable device SurGlove consisted of a pair of medical gloves, an OTS (Polaris Vicra, Northern Digital Inc., Canada) for tracking the retro-reflective markers within the field of view, an array of reflective spheres applied to a medical glove and distributed according to a strict mathematical pattern, a CH-340 development boar with ESP-8266 2.4 GHz WiFi modules, and a film pressure sensor (IMS-C07A, WAMX Inc, China).

The film pressure sensor was placed on the thumb of the glove to detect if the doctor is grabbing the instrument. The operating voltage of the film pressure sensor is 5V. When pressure is applied to the film pressure sensor, the higher the pressure, the lower its resistance. A grasping event was defined to trigger once the voltage of the pressure sensor would drop by 50%, indicating a grasping force of approximately 250 g. Then the embedded board will broadcast the signal to the computer via a user-datagram-program (UDP) protocol at a frequency of 150 Hz and turn on the OTS to track the retro-reflective markers to collect data. The OTS transmits the collected data to the computer, which calculates the spatial rotation and displacement of the operator's hand using the spatial rotation and translation matrices. Finally, the calculated spatial rotation angles and displacements are used to control the movement of the slave-robot in order to reach the target position.

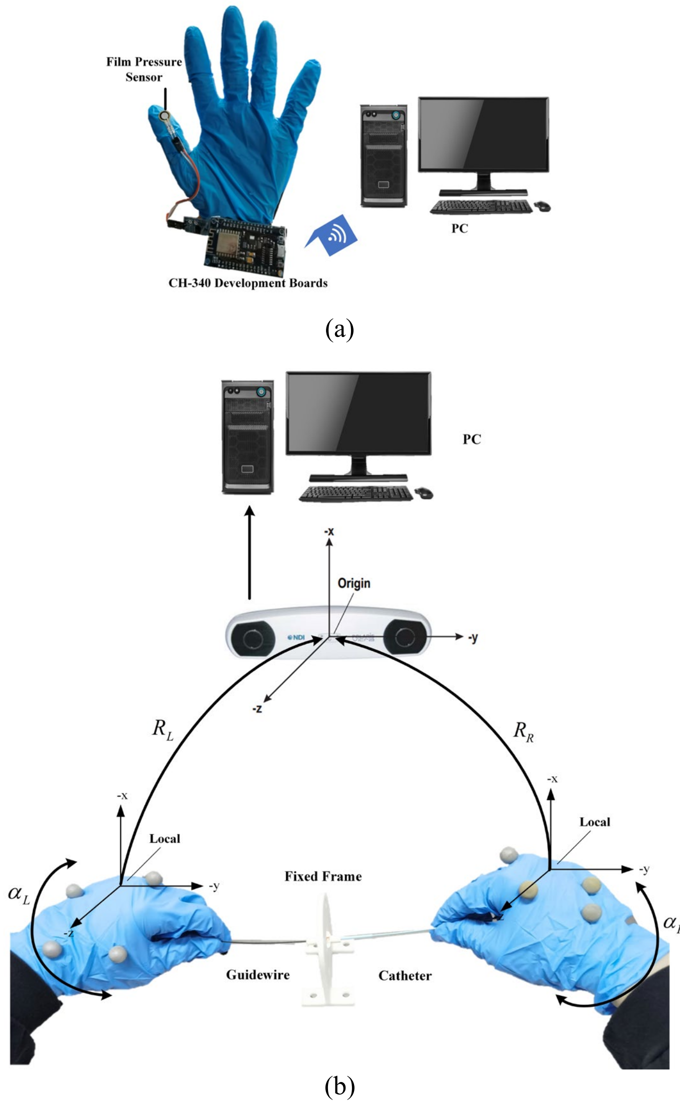

Fig. 1 The prototyped SurGlove with the film pressure sensor. (a) Film pressure sensor. (b) The schematic use-case of SurGlove and the coordinate conversion diagram.

OTS can't distinguish the tools with the same retro-reflective markers distribution. And in order to achieve accurate positioning, the OTS requires an array of retro-reflective markers to follow certain mathematical laws. So two different retro-reflective markers distributions were adopted as shown in Fig.2. The distribution of the retro-reflective markers in the right hand is shown in Fig.2(a) and the distribution in the left hand is shown in Fig.2(b). These reflective markers are attached to the medical gloves using a highly adhesive material, avoiding inaccurate positioning due to poorly attached spheres.

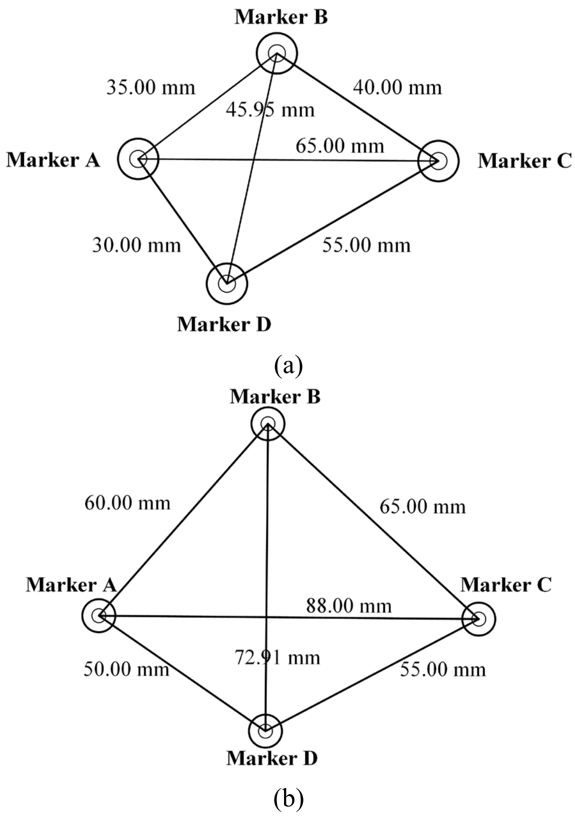

Fig. 2 Markers distribution information. (a) Right hand. (b) Left hand.

B. System Calibration

System calibration of the wearable device and OTS is the foundation of master-side manipulator application. The coordinate transformation relationship from the left and right-hand gloves to the OTS is calculated by calibration. Each coordinate system involved in the calibration needs to be defined before the registration of the device to facilitate subsequent mathematical calculations. Coordinate systems include a world coordinate system and a positioning device coordinate system.

In this paper, the world coordinate system is the optical positioner coordinate system, with the center of the positioner's eyes as the origin of the world coordinate system. The positioning device coordinate system consists of a plane consisting of four positioning spheres mounted on the instrument. The definition information of the localization device coordinate system needs to be pre-set before operation and all coordinate systems are designed in accordance with a strict mathematical derivation. After receiving the reflected infrared signals, the localizer is compared with the definition information to identify different localization devices and thus different instruments. The coordinate conversion relationship between the world coordinate system and the positioning device coordinate system is shown in Fig.1(b).

There are two types of coordinate conversion: translation and rotation. A coordinate system transformation can be expressed by a rotation vector and a translation vector. Any rotation of the coordinate system can be characterized by a rotation axis and a rotation angle. Thus, a rotation vector can be used so that its direction coincides with the axis of rotation and its length is equal to the angle of rotation. In practical calculations, the rotation is often around an arbitrary axis, requiring the use of the Rodriguez formula to calculate the rotation matrix by rotating vector. Suppose the vector $\vec{v}$ is rotated around the axis $\vec{Z}$ to obtain the new vector $\vec{v^{\theta}}$ as shown in Fig.3.

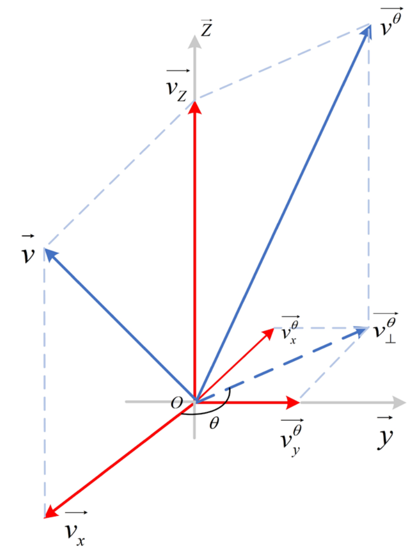

Fig. 3 Diagram of the arbitrary axis rotation.

At first, the orthogonal decomposition of $\vec{v}$ is obtained as

$$\vec{v} = \vec{v_a} + \vec{v_b} \,. \tag{1}$$

Through the projection relation of the vectors, the $\vec{v_a}$ and $\vec{v_b}$ are calculated as

$$\vec{v_b} = \left(\vec{v} \cdot \vec{Z}\right)\vec{Z} \tag{2}$$

$$\vec{v_a} = \vec{Z} \times \left(\vec{v} \times \vec{Z}\right). \tag{3}$$

$\vec{v_a}$, $\vec{Z}$ and $\vec{y}$ are perpendicular to each other, and $\left|\vec{v_a}\right| = \left|\vec{y}\right|$. Therefore, by using the Cross product of vectors, $\vec{y}$ is obtained as

$$\vec{y} = \vec{Z} \times \vec{v_a} = \vec{Z} \times (\vec{Z} \times (\vec{v} \times \vec{Z})) = \vec{Z} \times \vec{v} \,. \tag{4}$$

$\vec{v_a}$ has been rotated to get $\vec{v_{\perp}^{\theta}}$, decompose $\vec{v_{\perp}^{\theta}}$ orthogonally to get $\vec{v_x^{\theta}}$ and $\vec{v_y^{\theta}}$

$$\left|\vec{v_x^{\theta}}\right| = \left|\vec{v_{\perp}^{\theta}}\right| \times \cos(\theta - 90^{\circ}) = \left|\vec{v_{\perp}^{\theta}}\right| \times \sin\theta \tag{5}$$

$$\left|\vec{v_y^{\theta}}\right| = \left|\vec{v_{\perp}^{\theta}}\right| \times \cos(180^{\circ} - \theta) = -\left|\vec{v_{\perp}^{\theta}}\right| \times \cos\theta \,. \tag{6}$$

Given that $\left|\vec{v_{\perp}^{\theta}}\right| = \left|\vec{y}\right| = \left|\vec{v_x}\right|$, which results in

$$\overrightarrow{v_{\perp}^{\theta}} = \overrightarrow{v_x^{\theta}} + \overrightarrow{v_y^{\theta}} = \vec{y}\cdot\sin\theta + \overrightarrow{v_x}\cdot\cos\theta . \quad (7)$$

Therefore

$$\overrightarrow{v^{\theta}} = \overrightarrow{v_{\perp}^{\theta}} + \overrightarrow{v_z} = \cos\theta\cdot\vec{v} + (1-\cos\theta)(\vec{v}\cdot\vec{Z})\vec{Z} + \sin\theta\cdot\vec{Z}\times\vec{v} . \quad (8)$$

The $\vec{Z}$ and $\vec{v}$ were assumed with the form

$$\vec{Z} = (Z_x\ Z_y\ Z_z)^T \quad (9)$$

$$\vec{v} = (v_x\ v_y\ v_z)^T \quad (10)$$

the identification of $\vec{Z}$ and $\vec{v}$ constituted the equations as

$$(\vec{v}\cdot\vec{Z})\vec{Z} = \vec{Z}(\vec{Z}^T\cdot\vec{v}) \quad (11)$$

$$\vec{Z}\times\vec{v} = \begin{pmatrix} Z_y v_z - Z_z v_y \\ Z_z v_x - Z_x v_z \\ Z_x v_y - Z_y v_x \end{pmatrix} = \begin{pmatrix} 0 & -Z_z & Z_y \\ Z_z & 0 & -Z_x \\ -Z_y & Z_x & 0 \end{pmatrix}\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} . \quad (12)$$

To find the rotation matrix around the axis of interest is to find R in $\overrightarrow{v^{\theta}} = R\cdot\vec{v}$. Therefore, by using the equation (11) and (12) , (8) was reordered as

$$R = I\cos\theta + (1-\cos\theta)\begin{pmatrix} Z_x \\ Z_y \\ Z_z \end{pmatrix}\begin{pmatrix} Z_x & Z_y & Z_z \end{pmatrix} + \sin\theta\begin{pmatrix} 0 & -Z_z & Z_y \\ Z_z & 0 & -Z_x \\ -Z_y & Z_x & 0 \end{pmatrix} . \quad (13)$$

Combine the rotation matrix R with the translation matrix T to form the transformation matrix $Trans$ as

$$Trans = \begin{bmatrix} R_{3\times3} & T_{3\times1} \\ 0 & 1 \end{bmatrix}_{4\times4} . \quad (14)$$

III. Experimental Validation

Two experimental validation studies were completed to verify the proposed system's performance. The target of the two studies was to investigate the accuracy of the proposed device in rotation and translation estimation.

A. Study I: Rotation Estimation

Fig. 4 shows the experimental setup used in the validation study. In the experiment, the surgeon wore the SurGlove just like medical gloves in ordinary surgery and rotated a catheter as it would normally be done in a VIS procedure. The operator held the distal end of the catheter and the proximal end of the catheter is connected to the rotary encoder (E6B2-CWZ6C, Omron Co., Shanghai, China) via a coupling. The encoder measured the rotation angle of the catheter as the reference. The data is transmitted to the PC through an Arduino Mega. In the meantime, SurGlove recorded the surgeon's operational rotation angle. When the film pressure sensor activated the OST for data acquisition, the initial global orientation of SurGlove was recorded as offset and was deducted from the real-time angles to measure the relative change in the angles of SurGlove. In order to compare with the reference data, the spatial rotation angle α needs to be derived from the rotation matrix R acquired by the OTS.

The spatial angle is obtained as

$$\alpha = \arccos\left(\frac{Tr(R)-1}{2}\right) \quad (15)$$

where $Tr(\cdot)$ was the trace operator, which is the scalar summation of the major diagonal components of the matrix.

Fig. 5 shows the results of the validation experiment. The results demonstrate that the angle calculated by the glove is in considerable agreement with the reference value of the encoder. In this experiment, the surface facing the ground was defined as zero angle and clockwise rotation as the positive direction($\alpha > 0$). [18] mentioned that the normal range of motion of the human wrist joint pre- and post-rotation is 60◦and 140◦.Therefore, the range of α would translate to $\alpha \in [-60\ 140]$.

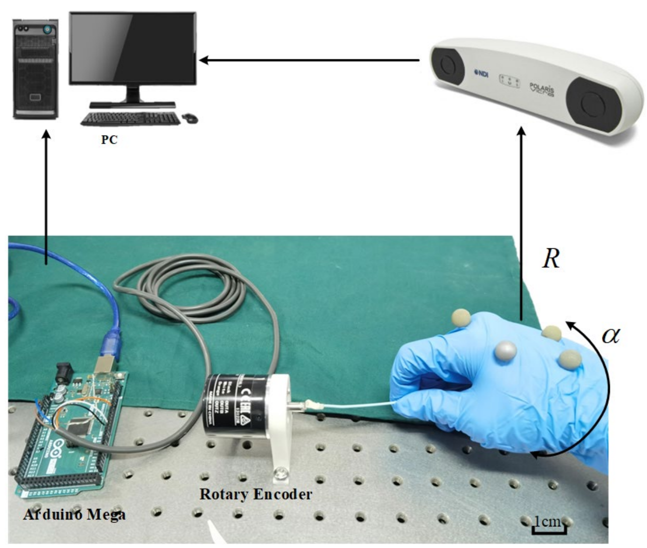

Fig. 4 Experimental Setup of Rotation Angle Validation Study.

There is a section of the SurGlove in the Fig.5 where no data was recorded, due to the fact that the optical locator may have been obscured or otherwise affected. This is the biggest drawback of the OTS. During surgery, a short loss of command does not affect the safety of the procedure, as the slave robot will stop operating due to lack of command. For a more objective response to the error, the missing data in this paragraph were therefore excluded and then compared. More specifically, the mean absolute error (MAE) of the SurGlove angles with respect to the reference was 1.88°, resulting in a maximum relative error of 1.05% of 180°. Such rotational measurement errors are a significant improvement over the methods in [6] and [11] are more promising for clinical application. In summary, SurGlove is competent to perform the job of rotational measurement of the manipulator master of the VIS robot.

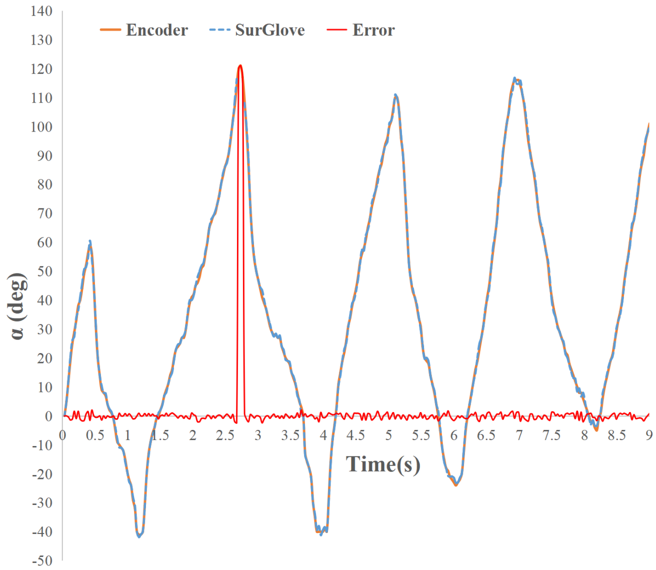

Fig. 5 Comparison of rotation angle measurement by SurGolve and the reference encoder.

B. Study II: Translation Estimation

In this part, the purpose of the experiments is to evaluate the translation estimation performance of the SurGlove. The experimental setup for the evaluation experiments is shown in Fig. 6, and consists of the pull line linear displacement encoder (E6B2-CWZ6C, Omron Co., Shanghai, China), OTS to track markers to acquire the displacement of the SurGlove and an Arduino Mega transmits encoder data to PC. In this experiment, the operator wore the SurGlove and pulled the encoder, and the optical positioner collected the spatial displacement of the operator's hands in real-time. The inner circumference of this pull line linear displacement encoder is 100*mm* and the maximum stretch length is 500*mm*.

In order to compare with the reference data, the spatial translation displacement L needs to be derived from the translation matrix T acquired by the OTS.

The spatial displacement is obtained as

$$L = |T_1 - T_2| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \,. \tag{16}$$

The results of the displacement validation experiment is shown in Fig.7. The results show that our method performs in good agreement with the reference when performing displacement measurements. The maximum error is around 5*mm* and stays below 2*mm* most of the time. More specifically, the MAE of the SurGlove displacement with respect to the reference was 1.53*mm*. The results demonstrate the ability of the SurGlove to assume the displacement measurement of the master manipulator of the vascular intervention surgical robotic system.

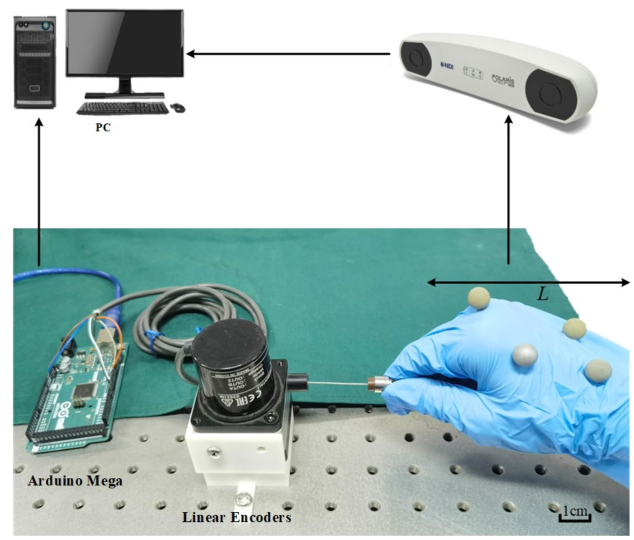

Fig. 6 Experimental Setup of Displacement Validation Study.

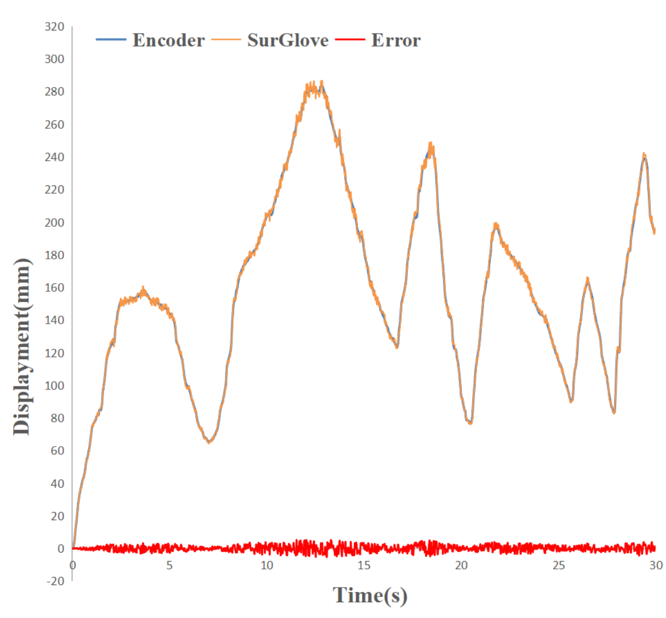

Fig. 7 Comparison of displacement measurement by SurGolve and the reference encoder.

IV. Conclusion

This study developed a wearable master manipulator SurGlove for VIS. The surgeon can wear the SurGolve as the common medical glove and handle the catheter and guidewire directly, which is in line with the surgeon's traditional operation and accumulated clinical experience. The wearable design reduces the impact of the master manipulator's inherent inertia on the tactile sensation of the surgeon's hands. It is of great help to improve the sense of presence when surgeons operate the master-slave VIS robotic system.

The validation experiment results indicated that the SurGlove can measure the rotation and displacement of the surgeon’s hands with a high accuracy and refresh rate. The data distribution of the validation experimental results is shown in Fig.5 and Fig.7. The evaluation experiments showed that the proposed device had an MAE of 1.88° and a maximum error of less than 3° in rotation angle measurement. The maximum displacement error was less than 5 mm and the MAE was 1.53 mm.

In addition, the proposed device simplifies the complex structure of traditional master manipulators. For example, conventional master manipulators are manufactured in such a way that the coaxial positioning relationship must be guaranteed to ensure the operational accuracy of the main manipulator. However, absolute coaxial positioning is very difficult to achieve and there will always be a certain amount of error.

However, there are some limitations in this study. Firstly, as the OST requires tracking markers for positioning, this may not work if the light is obscured. To overcome this limitation, the use of a user interface and vibration to alert the operator that OTS tracking has failed could be considered in the future. Secondly, SurGlove currently handles the rotation of the catheter and guidewire by detecting the rotation of the operator's wrist. In the future, a motion capture camera could be considered to track marker points fixed to the index finger and thumb, calculating the relative motion of the two fingers to control the rotation of the guidewire and catheter. Finally, the SurGlove lacks a force feedback device to give the operator the force on the guidewire and catheter during the operation. [19] and [20] mentioned that many experiments have shown that master manipulator with force feedback can improve safety and reduce the duration of the operation. In future studies, the focus will be on how to add non-contact force feedback methods, such as electromagnetic forces, to SurGlove. In conclusion, the SurGlove is still not perfect now and much work remains to be done to improve it. However, this study still provides a new idea for future research on the master manipulator for vascular interventional robotic systems.

REFERENCES

[1] G. W. Britz, J. Tomas, and A. Lumsden, "Feasibility of robotic-assisted neurovascular interventions: Initial experience in flow model and porcine model," *Neurosurgery*, vol. 86, no. 2, pp. 309–314, 2020.

[2] X. Yin, S. Guo, H. Hirata, and H. Ishihara, "Design and experimental evaluation of a teleoperated haptic robot–assisted catheter operating system," *J. Intell. Mater. Syst. Struct.*, vol. 27, no. 1, pp. 3–16, Jan. 2016.

[3] S. Guo, Y. Song, and X. Yin, "A novel robot-assisted endovascular catheterization system with haptic force feedback," *IEEE Trans. Robot*, vol. 35, pp. 685–696, Mar. 2019.

[4] T. M. Patel, S. C. Shah, Y. Y. Soni, et al., "Comparison of robotic percutaneous coronary intervention with traditional percutaneous coronary intervention: A propensity score–matched analysis of a large cohort," *Circulat., Cardiovascular Interventions,* vol. 13, no. 5, pp. 1941–7632, May 2020.

[5] E. M. Khan, W. Frumkin, G. Ander. Ng, et al., "First experience with a novel robotic remote catheter system: Amigo mapping trial," *J. Intervent. Cardiac Electrophysiol.*, vol. 37, no. 2, pp. 121–129, 2013.

[6] A. Hooshiar, A. Sayadi, J. Dargahi, et al., "Integral-free spatial orientation estimation method and wearable rotation measurement device for robot assisted catheter intervention," *IEEE/ASME Trans. Mechatronics*, vol. 27, pp. 766–776, 2022.

[7] Y. Yan, H, Wang, H. Yu, et al., "Machine Learning-Based Surgical State Perception and Collaborative Control for a Vascular Interventional Robot," *IEEE Sensors Journal*, vol.22, no.7, pp.7106-7118, April. 2022.

[8] X. Bao, S. Guo, L. Shi, and N. Xiao, "Design and evaluation of sensorized robot for minimally vascular interventional surgery," *Microsyst. Technol.*, vol. 25, no. 7, pp. 2759–2766, 2019.

[9] X. Bao, S. Guo, Y. Guo, et al., "Multilevel Operation Strategy of a Vascular Interventional Robot System for Surgical Safety in Teleoperation," *IEEE Trans. Robot*, vol.38, no.4, pp.2238-2250, Aug. 2022.

[10] H.-J. Cha, B.-J. Yi, and J. Y. Won, "An assembly-type master–slave catheter and guidewire driving system for vascular intervention," *Proc. Inst.Mech.Eng., H,J.Eng.Med.*, vol. 231, no. 1, pp. 69–79, Jan. 2017.

[11] W. Zhou, S. Guo, J. Guo, et al, "A Surgeon's Habits-Based Novel Master Manipulator for the Vascular Interventional Surgical Master-Slave Robotic System," *IEEE Sensors Journal*, vol. 22, no. 10, pp. 9922-9931, May. 2022.

[12] L. Zhang, S. Guo, H. Yu, et al., "Design and performance evaluation of collision protection-based safety operation for a haptic robot-assisted catheter operating system," *Biomed. Microdevices*, vol. 20, no. 2, pp. 1–14, Jun. 2018.

[13] X. Li, S. Guo, P. Shi, et al., "An Endovascular Catheterization Robotic System Using Collaborative Operation with Magnetically Controlled Haptic Force Feedback," *Micromachines*, vol.13, no.4, pp.505-517, Mar. 2022.

[14] G. Dagnino, J. Liu, M. E. Abdelaziz, et al., "Haptic feedback and dynamic active constraints for robot-assisted endovascular catheterization," *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 1770–1775, 2018.

[15] G. Zhou, X. Chen, B. Niu, et al., "Intraoperative localization of small pulmonary nodules to assist surgical resection: a novel approach using a surgical navigation puncture robot system," *Thoracic Cancer.*, vol.11, no.1, pp.72-81, 2020.

[16] B. Yan, W. Zhang, L. Cai, et al., "Optics-guided Robotic System for Dental Implant Surgery," *Chinese Journal of Mechanical Engineering.*, vol.35, no.3, pp.55-68, 2022.

[17] P. Tu, C. Qin, Y. Guo, et al., "Ultrasound Image Guided and Mixed Reality-Based Surgical System With Real-Time Soft Tissue Deformation Computing for Robotic Cervical Pedicle Screw Placement," *IEEE Trans. Biomed. Eng.,* vol.69, no.8, pp.2593-2603, 2022.

[18] T. S. Kim et al., "A study on the measurement of wrist motion range using the iPhone 4 gyroscope application," *Ann. Plastic Surg.*, vol. 73, no. 2, pp. 215–218, 2014.

[19] X. Jin, S. Guo, J. Guo, P. Shi, et al., "Development of a tactile sensing robot-assisted system for vascular interventional surgery," *IEEE Sensors Journal*, vol. 21, no. 10, pp. 12284–12294, 2021.

[20] X. Jin, S. Guo, J. Guo, et al., "Total force analysis and safety enhancing for operating both guidewire and catheter in endovascular surgery," *IEEE Sensors Journal*, vol. 21, no. 20, pp. 22499–22509,2021.