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Development of a Novel Remote Controller for Interventional Surgical Robots

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***Abstract* - Interventional surgical robot is the advance method of performing interventional surgery. The master-slave system structure not only prevent surgeon from radiation, but also create a stable operation environment for the patients. Based on our lab previous research, this paper presents a novel remote controller for interventional surgical robots, and evaluate its displacement measuring system accuracy through experiments. The novel controller is smaller and more maneuverable compared to the controller in our previous research. According to the performance evaluation experiments, the novel controller has the ability to collect data efficiently and accurately.**

Index Terms –Interventional surgical robot; Master-slave surgical robot; Remote controller;

I. INTRODUCTION

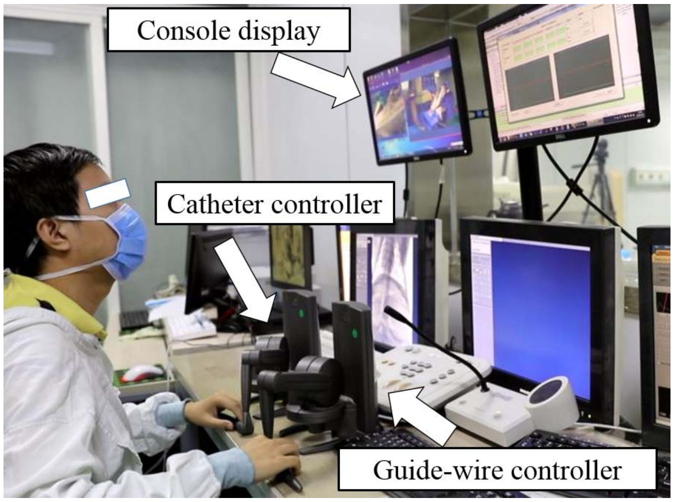
As a new treatment of the cardiovascular disease, the interventional surgery has been widely used across the world. Comparing to the traditional open surgery, interventional surgery has the advantage of less bleeding, low infection rate, and quick recovery after surgery. The surgeon use guide-wire as a director and operate the catheter to the target area. Then provide different treatment such as stent or balloon through the catheter. Although this type of surgery reduced patient suffering in many ways, it brings great challenge to the surgeon. The interventional surgery needs the support of X-ray. The surgeon have to expose under the radiation in order to observe the surgery condition when operating the catheter and guide-wire. Even the surgeon wears radiation protection clothing while performing the surgery, the radiation will still cause serious damage considering the number of surgery the surgeon performs per day. Besides the radiation, wearing lead apron day by day will also cause shoulder and back strain, which not only harms the surgeon, but also affect the surgery performance as well.

In the context of application demand, the interventional surgical robot comes to be a heat area of research. The interventional surgical robots usually have two parts: the mater side and the slave side. This design purpose is to let surgeons operate the master side outside the operation room, and the slave side performs the operation for patients under the instruction of the master side. Which will not only reduce the radiation harm but also provide a stable operating condition for the patients.

Many universities and research institutions have put in effort in developing interventional surgical robot. Recent years researchers such as Prof. Fu and his team from Harbin Institute of Technology developed a haptic device for minimally invasive surgery [1]; Prof. Guo and his team from Beijing Institute of Technology developed an interventional surgical robot which achieved the coordinated operation of the catheter and the guide-wire [2-10]. Dr. Park in Korea University also developed a 3-DOF cardiac ablation catheter operating system [11]. Besides University researches, many commercial products in this field have been invented and put into use. For example, Hansen Medical's Sensei robot can enhance the stability of doctors' operations while isolating doctors from the radiation area [12]. The Amigo operating system produced by Catheter Robotic has similar functions as the Sensi robot [13]. The CGCI system produced by Magnatecs operates a special catheter for surgery by controlling the magnetic field environment. Others include the Niobe robot developed by Stereotaxis [14], and the interventional robot developed by Yogesh Thakur [15]. These robots can preserve the habits of doctors to a certain extent and provide remote operation for surgeons.

In our previous research, we developed an interventional surgical robot which accomplished in vivo experiment [16], the master side and slave side are shown in Fig.1. But there are still improvements we can achieve. For example, the controller we used as the master controller is a well-developed haptic interaction device called Touch X (Geomagic®Touch, 3D Systems, Inc., USA). This haptic device contains multiple degrees of freedom and has displacement limit in each degrees, which is different from operating catheter or guide-wire. This differences not only makes the surgeon spend more time on figure out the operation method of the device, but also affect the application of surgeon’s operation skills. Furthermore, the heavy outer casing and oversized volume made it hard to adjust during the operation.

Under these circumstances, this paper presents a novel remote controller for interventional surgical robots, which not only has the function to collect surgeon’s operation data and create force feedback, but also smaller and more maneuverable compared to the master side we use. This paper will mainly focus on its linear and rotation measurement and



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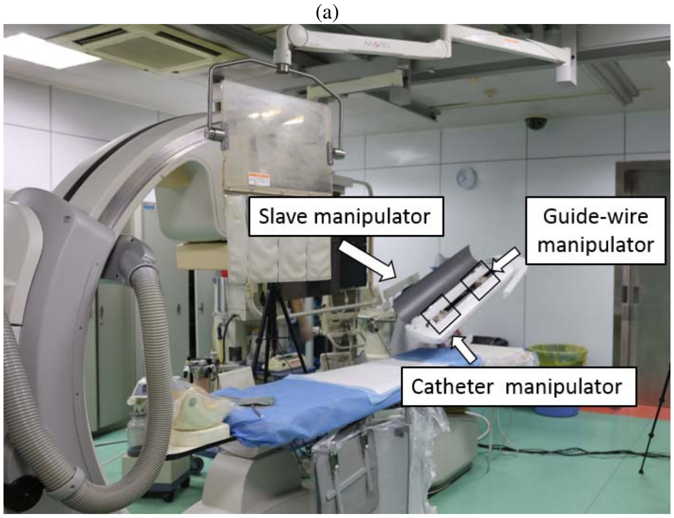

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Fig.1 The interventional surgical robot developed by Guolab.
(a) master side: remote controller; (b) slave side: controlled robot.

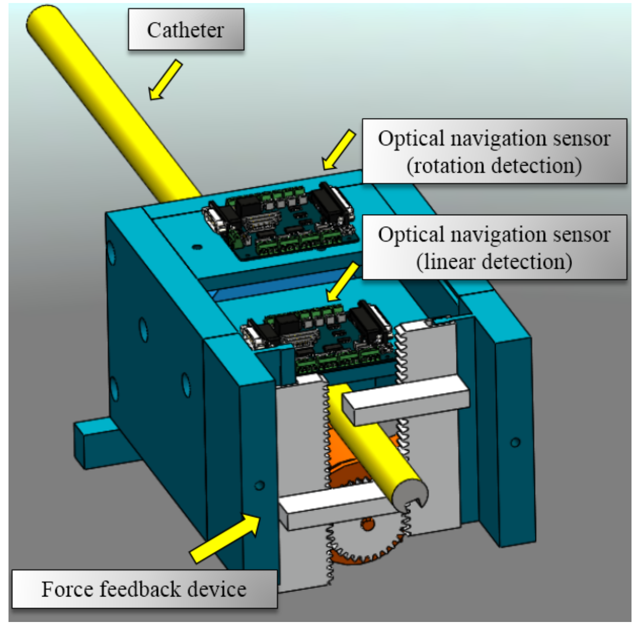


Fig.2 Virtual prototype of the proposed remote controller.

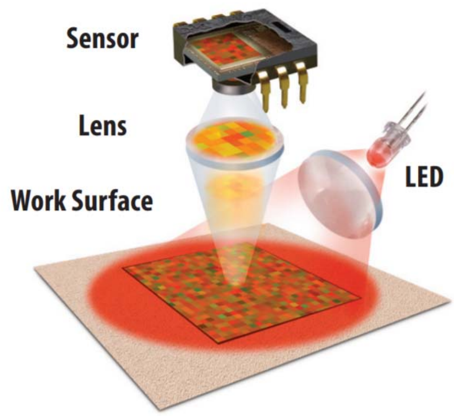


Fig.3 Working principle of the optical navigation sensor.

evaluate its displacement measuring system accuracy through experiments.

II. Controller Description

The operation habit of surgeon usually come from three aspect [17-20]:

1) Advance and retreat: to move catheter or guide-wire through the blood vessel;

2) Rotation: to change direction of the catheter or guide-wire in the blood vessel;

3) Cooperation of linear movement and rotation: to select the target vessel through narrow blood branches.

According to the operation habit, the master controller must collect the operation data of linear and rotation movement, and create force feedback for the surgeon to avoid collision between catheter and blood vessel during the operation.

A. Design of the Novel Remote controller

The remote controller shown in Fig.2 is composed of three parts: a rotation detection device, a linear detection device, and a force feedback device. The surgeon can complete the linear and rotating control and feel the force feedback generated by the frictional resistance.

The linear and rotation data are detected by optical navigation sensor respectively. The working principle of the optical navigation sensor is shown in Fig.3: when the surgeon operates the catheter, the led or laser will illuminates the work surface, and optical navigation sensor begins to scan the patterns and transfer thousands of pictures per second to the digital signal processor (DSP) [21-22]. The processor then calculate the direction and moving distance by comparing the differences between successive images. The novel controller is designed to be the similar structure for the surgeon to operate catheter or guide-wire in the operation room. The surgeon is able to freely advance and retreat the catheter, and rotate the catheter over 360 degrees. Comparing to commercial products like Phantom and omega, the optical navigation sensor has a smaller size and equal or higher level of precision. In addition, controllers like Phantom and omega makes it impossible to build an isomorphic structure for master-slave interventional

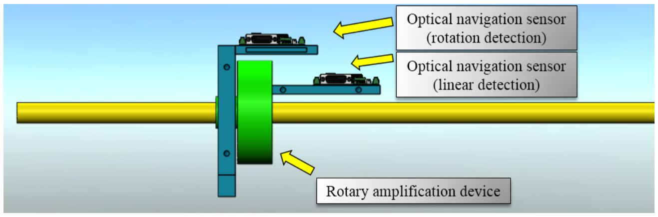


Fig.4 Working diagram of measuring the linear and rotation displacement through optical navigation sensor.

robot, which will force the surgeon to get familiar with the machine before the operation. Furthermore, the operation freedom of products like Phantom and omega is too high and the work space is limited, the catheter and guide-wire surgical technique cannot be applied to the remote control.

The force feedback device of the proposed remote controller is composed of a motor and a clamping device. The clamping device is designed to mimics the gripping motion of the thumb and index finger. The clamping device is driven by the motor through rack and pinion. Through calculation, we can control the clamping and relaxation of the clamping device by adjusting the rotation angle of the motor shaft. The portion of the clamping device that grips the catheter is equipped with tactile sensor, which will reflects the pressure exerted by the clamping device on the catheter. Through the connection between positive pressure and friction, we can create a friction force feedback for the operator by adjusting the motor [23-26].

According to the introducing brochure, the device volume of the controller we use at present Geomagic®Touch X is 160 W * 120 H * 120 D mm. The device volume of the proposed controller is 118 W * 70 H *81 D mm, which is much smaller.

B. Calibration of Controller Displacement Measurement

The working diagram of measuring the linear and rotation displacement through optical navigation sensor is shown in Fig.4. The movement data is calculated by the direction and moving distance by comparing the differences between successive images. In order to achieve accurate measurements, linear and rotations are measured using individual optical sensors. Due to the small radius of the catheter, in order to improve the accuracy of the rotation measurement, the radius of the catheter is amplified by a rotary amplifying device, to approximately transfer the rotational motion as a linear motion perpendicular to the direction of catheter movement. The data of catheter movement can be calculated using the following two formulas:

$$\Delta X = \Delta P_x * \frac{1}{\lambda} \tag{1}$$

$$\begin{cases} \Delta\theta_y = 360^\circ * \dfrac{\Delta y}{2\pi * r} * \dfrac{1}{\lambda} \\ \Delta y = \Delta P_y * \dfrac{1}{\lambda} \end{cases} \tag{2}$$

The calibration principle for of measuring the linear and rotation displacement is show in Fig.5, where ΔP_x and ΔP_y are the number of pixel changes received by the optical sensors in different directions when the surgeon operates. λ is the resolution of the sensor. The counts per inch (CPI) of the sensor in our case is 800, which means λ is 0.03175mm. For every 0.03175mm the catheter moves in linear or rotation direction, the sensor will detect a pixel and generate a count. Δx and Δθy are the linear and rotation movement result we acquire. r is the radius of the rotary amplifying device.

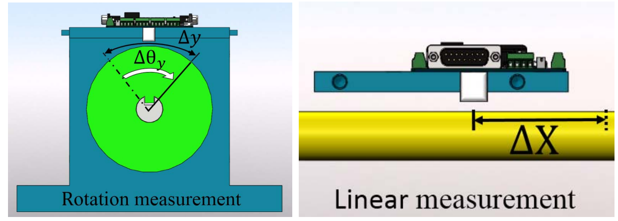
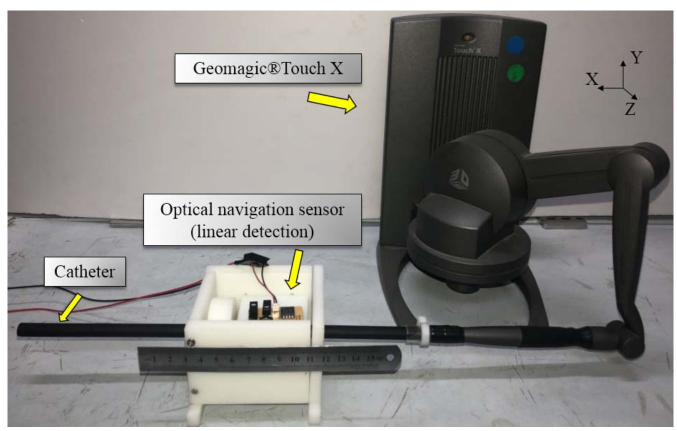


Fig.5 Calibration principle of measuring the linear and rotation displacement.

III. Evaluation Experiment

In order to evaluate the accuracy of the data collection by the novel master system, we designed two evaluation experiment. The experimental setup for linear and rotation accuracy evaluation is shown in Fig.6.

To evaluate linear accuracy, the catheter is fixed to the Geomagic®Touch X operate bar. The Geomagic®Touch X is connected to the computer through Ethernet [27-29]. The optical sensor is first connected to the data processor through wireless radio frequency, then upload the data to the computer through serial port. In order to ensure the accuracy of the experiment, two controllers are placed in parallel before the experiment, ensure the X axis of Geomagic®Touch X coincides with the linear displacement direction of the



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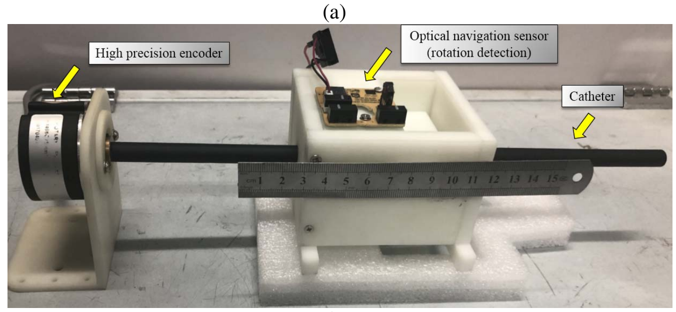

(b)

Fig.6 Experimental setup for linear and rotation accuracy evaluation. (a) Linear accuracy evaluation; (b) Rotation accuracy evaluation.

catheter. By operating the catheter, the optical sensor and the Geomagic®Touch X detected the same amount of linear displacement.

Since the rotation range of Geomagic®Touch X operate bar is between 0 to 300 degrees, the rotation evaluation can't full achieved by connecting the catheter to the Geomagic®Touch X. Therefore we use a high precision encoder to evaluate the rotation accuracy. The encoder resolution is 2048 pulse per round, which means the minimum angle change that the encoder can detect is 0.17°. According to the previous in vivo experiments, this resolution meets the requirements for the surgeon to operate catheter and guide-wire. The encoder is fixed with the catheter that detected by the optical sensor through the rotary amplifying device. By comparing the rotation angles detected by the encoder and sensor during coaxial rotation, the rotation accuracy can be evaluated.

IV. Results and Discussions

Since the main controller is operated by a surgeon manually, we performed the evaluation experiments based on the operation habit at which the doctor performed the linear and rotational movement during the animal experiments in the previous study. The experimental process is shown in Fig.7, each experiment was carried out ten times. Limited by the length of the prototype catheter (300mm), the linear evaluation experiments moving distance were less than 300mm. Furthermore, since the tip of the Geomagic®Touch X control bar is an arc-shaped structure, there may be gaps at the rigid joint between the catheter and the Geomagic®Touch X, which may cause relative movement. Therefore, to avoid the relative movement error caused by forward-backward operation, the linear experiment only moved in a single direction when operating the catheter. The average operation error of linear experiments is 0.22mm, which meets the requirements for surgeons to operate catheter and guide-wire accurately according to previous in vivo experiments. Unlike linear experiments, the catheter is firmly fixed with encoder, so the catheter rotated both clockwise and counterclockwise during each evaluation. The average rotation error of rotation experiments is 0.97°, which also meets the requirements for surgeons to operate catheter and guide-wire accurately according to previous in vivo experiments.

According to the analysis, the error mainly occurs in two aspects: First is that during the linear displacement experiment, the distance between the catheter and the optical sensor changes when the catheter is operated, causing the sensor sampling to be affected. Second is that during the rotation experiment, although the rotation of the catheter is amplified, the sensor is still affected by the rotation angle during the measurement, and the measured value is inconsistent with the actual circumference of the rotation, which means a rotation displacement compensation is required. Moreover, when the operator controls the catheter, the operator's unconscious tremble will vary distance between the catheter and the optical navigation sensor, affect the accuracy of measurement results in some extent.

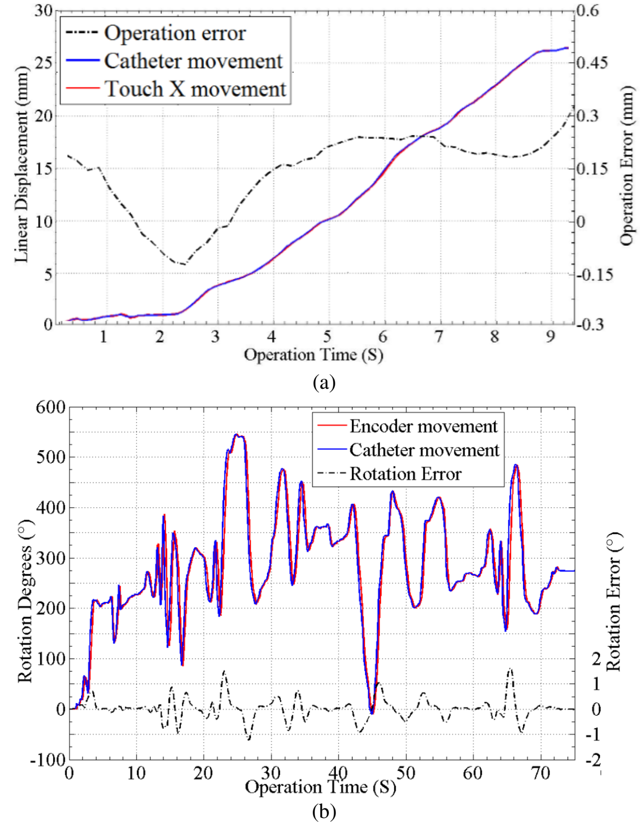

Fig.7 Experimental result for linear and rotation accuracy evaluation. (a) Linear evaluation result; (b) Rotation evaluation result.

V. Conclusion and Future Work

In this paper, a novel remote controller for interventional surgical robot is proposed. The prototype structure and the controller function including linear/rotation movement detection and force feedback is demonstrated in the upper page. This paper mainly focused on controller's linear and rotation movement detection method. The accuracy evaluation experiments shows that the proposed controller can meet the requirements of the master side movement detection.

However, there are still improvements we can achieve. For example the rotation detect accuracy has to improve, and we need to figure out the rotation displacement compensation coefficient.

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References

[1] T. Wang, B. Pan, and Y. Fu, "Design of a new haptic device and experiments in minimally invasive surgical robot". *Computer Assisted Surgery*, vol. 1, no. 11, 2017.

[2] X. Bao, S. Guo, N. Xiao, Y. Li, and L. Shi, "Compensatory force measurement and multimodal force feedback for remote-controlled

vascular interventional robot," *Biomedical Microdevices,* vol. 20, no. 3, 2018.

[3] X. Bao, S. Guo, L. Shi, and N. Xiao, "Design and evaluation of sensorized robot for minimally vascular interventional surgery," *Microsystem Technologies,* https://doi.org/10.1007/s00542-019-04297-3, 2019.

[4] Y. Wang, S. Guo, N. Xiao, Y. Li, and Y. Jiang, "Surgeons' Operation Skill-Based Control Strategy and Preliminary Evaluation for a Vascular Interventional Surgical Robot," *Journal of Medical and Biological Engineering,* https://doi.org/10.1007/s40846-018-0453-3, 2018.

[5] Y. Song, S. Guo, X. Yin, L. Zhang, H. Hirata, H. Ishihara, and T. Tamiya, "Performance evaluation of a robot-assisted catheter operating system with haptic feedback," *Biomedical Microdevices,* vol. 20, no. 2, 2018.

[6] Q. Fu, S. Zhang, S. Guo, and J. Guo, "Performance Evaluation of a Magnetically Actuated Capsule Microrobotic System for Medical Applications," *Micromachines,* vol. 9, no. 12, 2018.

[7] S. Guo, Y. Song, X. Yin, L. Zhang, T. Tamiya, H. Hirata, and H.Ishihara, "A Novel Robot-Assisted Endovascular Catheterization System with Haptic Force Feedback", *The IEEE Transactions on Robotics*, DOI: 10.1109/TRO.2019.2896763, 2019.

[8] S. Guo, C. Yang, X. Bao, N. Xiao, and R. Shen, "Characteristic Evaluation of a Master-Slave Interventional Surgical Robot Control system," *In Proceedings of the 2018 IEEE International Conference on Robotics and Biomimetics*, pp.421-425, DOI: 10.1109/ROBIO.2018.8665224, 2018.

[9] S. Guo, C. Yang, X. Bao, and N. Xiao, "A Novel Design of Grasper for the Interventional Surgical Robot," *In proceedings of the 2017 IEEE International Conference on Mechatronics and Automation*, pp.469-473, 2017.

[10] X. Yin, S. Guo, N. Xiao, T. Tamiya, H. Hirata, H. Ishihara, "Safety operation Consciousness Realization of MR Fluids-base Novel Haptic Interface for teleoperated Catheter Minimally Invasive neuro Surgery" *IEEE/ASME Transactions on Mechatronics*, Vol.21, No.2, pp.1043-1054, DOI:10.1109/TMECH.2015.2489219, 2015.

[11] J. Park, J. Choi, H. Pak, S. Song, J. Lee, Y. Park, S. Shin, and K. Sun, "Development of a force-reflecting robotic platform for cardiac catheter navigation," *Artificial Organs*, vol. 34, no. 11, pp. 1034–1039, 2010.

[12] C. Riga, C. Bicknell, A. Rolls, N. Cheshire, and M. Hamady, "Robot-assisted fenestrated endovascular aneurysm repair (FEVAR) using the Magellan system," *Journal of Vascular and Interventional Radiology,* vol. 24, no.2, pp. 191–196, 2013.

[13] E. Khan, W. Frumkin, G. Ng, S. Neelagaru, F. Abi-Samra, J. Lee, M. Giudici, D. Gohn, R. Winkle, J. Sussman, B. Knight, A. Berman, and H. Calkins, "First experience with a novel robotic remote catheter system: Amigo™ mapping trial," *Journal of Interventional Cardiac Electrophysiology*, vol. 37, no. 2, pp. 121-129, 2013.

[14] M. Faddis, W. Blume, J. Finney, A. Hall, J. Rauch, J. Sell, K. Bae, M. Talcott, and B. Lindsay, "Novel, magnetically guided catheter for endocardial mapping and radiofrequency catheter ablation," *Circulation,* vol. 106, no. 23, pp. 2980–2985, 2002.

[15] Y. Thakur, J. Bax, D. Holdsworth, and M. Drangova, "Design and performance evaluation of a remote catheter navigation system," *IEEE transactions on biomedical engineering*, vol. 56, no. 7, pp. 1901-1908, 2009.

[16] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang, R. Shen, J. Cui, Y. Jiang, X. Liu, and K. Liu, "Operation evaluation in-human of a novel Remote-controlled vascular interventional robot," *Biomedical Microdevices*, https://doi.org/10.1007/s10544-018-0277-5, 2018.

[17] R.Taylor and D. Stoiariovici, "Medical robotics in computer-integrated surgery," *IEEE Transactions on Robotics & Automation*, vol. 19, no. 5, pp. 922-926, 2003.

[18] R. Beyar, L. Gruberg, D. Deleanu, A. Roguin, Y. Almagor, S. Cohen, G. Kumar, and T. Wenderow, "Remote-control percutaneous coronary interventions: concept, validation, and first-in-humans pilot clinical trial," *Journal of the American College of Cardiology*, vol. 47, no. 2, pp.296-300, 2006.

[19] F. Arai, R. Fujimura, T. Fukuda, and M. Negoro, "New catheter driving method using linear stepping mechanism for intravascular neurosurgery," *In Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, vol. 3, pp. 2944-2949, 2002.

[20] R. Beyar, L. Gruberg, D. Deleanu, A. Roguin, Y. Almagor, S. Cohen, G. Kumar, and T. Wenderow, "Remote-control percutaneous coronary interventions: concept, validation, and first-in-humans pilot clinical trial," *Journal of the American College of Cardiology*, vol. 47, no. 2, pp. 296-300, 2006.

[21] J. Guo, S. Guo, "A Marker-based Contactless Catheter-sensing Method to Detect Surgeons' Operations for Catheterization Training Systems," *Biomedical Microdevices*, Vol.20, No.3, https://doi.org/10.1007/s10544-018-0321-5, 2018.

[22] J. Guo, M. Li, P. Ho, "Design and Performance Evaluation of a Force/Torque Sensor for Tele-Operated Catheterization Procedures," *IEEE Sensors Journal*, vol. 16, no. 9, pp. 1-1, 2016.

[23] X. Yin, S. Guo, Y. Song, "Magnetorheological fluids actuated haptic-based teleoperated catheter operating system", *Micromachines*, Vol.9, No.9, DOI: 10.3390/mi9090465, 2018

[24] S. Guo, Y. Wang ,N. Xiao, Y. Li, Y. Jiang, "Study on Real-time Force Feedback with a Master-slave Interventional Surgical Robotic System", *Biomedical Microdevices*, Vol.20, No.2, DOI: 10.1007/s10544-018-0278-4, 2018

[25] Y. Zhao, S. Guo, N. Xiao, Y. Wang, Y. Li, Y. Jiang, "Operating Force Information On-line Acquisition of a Novel Slave Manipulator for Vascular Interventional Surgery", *Biomedical Microdevices*, Vol.20, No.2, DOI:10.1007/s10544-018-0275-7, 2018

[26] J. Guo, X. Jin, S. Guo, "Study of the Operational Safety of a Vascular Interventional Surgical Robotic System", *Micromachines*, Vol.9, No.3, DOI:10.3390/mi9030119, 2018

[27] L. Zhang, S. Guo, H. Yu, Y. Song, T. Tamiya, H. Hirata, H. Ishihara, "Design and performance evaluation of collision protection-based safety operation for a haptic robot-assisted catheter operating system", *Biomedical Microdevices*, Vol.20, No.2, DOI:10.1007/s10544-018-0266-8, 2018

[28] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang, Y. Jiang, "A Cooperation of Catheters and Guidewires-based Novel Remote-Controlled Vascular Interventional Robot", *Biomedical Microdevices*, Vol.20, No.1, DOI:10.1007/s10544-018-0261-0, 2018

[29] Y. Wang, S. Guo, N. Xiao, Y. Li, Y. Jiang, "Online Measuring and Evaluation of Guidewire Inserting Resistance for Robotic Interventional Surgery Systems", *Microsystem Technologies*, Vol.24, No.8, pp.3467-3477, DOI:10.1007/s00542-018-3750-4, 2018