A Robot-assisted Endovascular Catheterization System with Haptic Feedback

by

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Abstract

Short recovery time, a small incision to the health issue, good surgical outcomes and little post-operative pain have facilitated the adoption of endovascular surgical techniques to diagnose and treat some cardiovascular and cerebrovascular diseases. Despite advantages over open surgery, conventional endovascular surgery has some limitations. First, the long fluoroscopy times and X-ray radiation exposure to physicians lead to problems like cancers and cataracts. Secondly, physicians overwhelmingly rely on 2-D visual feedback, which the information on the 3-D vasculature is lost to the physicians. Thirdly, the information of catheter tip-vessel contact can hardly be obtained by the operator. Fourthly, due to the high flexibility and non-smooth behavior of the catheter, accurate positioning of the catheter is difficult to realize by convention operating.

In recent two decades, the development of robotic catheter operating system was motivated by the desire to reduce fluoroscopy time, radiation dosage to surgeon and patient in addition to a reduction of surgeon fatigue, and improvement of position accuracy of the catheter. Despite their increased application and interest in this area, most of such systems have been designed without considering the natural behavior and motion patterns of experienced operators during the conventional endovascular procedures. Exiting studies on haptic feedback in robotic cauterization practices have been very limited.

Inspired by such motivations, this thesis proposes a robot-assisted endovascular catheterization system which can provide haptic feedback to the operator via the input catheter manipulation. To implementation this, firstly, a dynamic model of catheter intervention is established to reflect the interactions between the catheter and vasculature. The catheter tip force sensor has been developed to measure the catheter tip-vessel force. The 'pseudo collision' and 'real collision' are utilized to descript the catheter tip-vessel collision. Secondly, the haptic shared controlled architecture is presented for the robotic endovascular procedure. The catheter tip-vessel contact situations are adjusted to generate the haptic force. The results illustrate that haptic shared control has a benefit for improving catheter operational skills, as well as reducing the cognitive workload of operators. Thirdly, an MR fluids-based master haptic interface is presented. It can provide the physicians with the ability to use their conventional bedside skills during the robotic endovascular procedure. To achieve a quick response to haptic feedback, a novel hall sensor-based closed-loop control scheme was proposed. Meanwhile, the catheter manipulator with a novel miniaturized proximal sensing unit, as the slave robot, is proposed to actuate the patient catheter in traditional ways (push, pull, and rotate) and measure the contact force between the catheter and vasculature. Finally, to verify the efficacy of the proposed haptic guidance method, the evaluation experiments *in vitro* are carried out. The results demonstrate that the proposed robot-assisted endovascular catheterization system has the ability to enable decreasing the contact forces between the catheter and vasculature.

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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Chapter 1 Introduction

1.1 Challenges of Conventional Endovascular Procedures

The cardiovascular disease was the major cause of mortality in developed countries, about 34% of death each year [1]. The two main reasons of the cardiovascular disease are atherosclerosis and the narrowing of blood vessels [2]. The treatment of those diseases has been gone from open surgery techniques to minimally invasive intervention. Minimally invasive endovascular surgery is accomplished through the use of catheters and guidewires that inserted percutaneously via the artery into target lesions.

1.1.1 Conventional Endovascular Procedures

Short recovery time, a small incision to the health issue, good surgical outcomes and little post-operative pain have facilitated the adoption of endovascular surgical techniques to diagnose and treat some cardiovascular and cerebrovascular diseases [3]. In conventional endovascular surgeries, for manipulating catheters and guidewires through vasculature system of the body, the physician has to rely on visual and haptic sensation obtained from 2D fluoroscopy and the sensed forces at the fingertips [4]. The navigation is achieved using the motion of insertion, retraction, and rotation at the proximal end of the catheters and guidewires [5].

1.1.2 Clinical Challenges

Despite advantages over open surgery, conventional endovascular surgery has limitations. First, the long fluoroscopy times and X-ray radiation exposure to physicians lead to problems like cancers and cataracts [6]. Even though lead aprons are worn, the face and hands are still in exposure. The heavy protection suits with long hours in the operating can lead to neck and back pain and injure [7]. Secondly, physicians overwhelmingly rely on 2-D visual feedback, as one of their dominant information sources, which the information on the 3-D vasculature is lost to the physicians [8]. Thirdly, the information of catheter tip-vessel contact can hardly be obtained by the operator [9]. The friction force between the catheter and the introducer sheath has an influence on tactile sensations felt by the surgeon when manipulating the catheters [10]. Fourthly, due to the high flexibility and non-smooth behavior of the catheter, accurate positioning of the catheter is difficult to realize [5].

1.2 Robotics Technology for Endovascular Procedures

In recent two decades, the development of robotic catheter operating system was motivated by the desire to reduce fluoroscopy time, radiation dosage to surgeon and patient in addition to a reduction of surgeon fatigue, and improvement of position accuracy of the catheter [4]. Unlike the conventional bedside technique, the robotic catheter operating system allows the physician to offer an axial and radial motion on master robot placed in a remote location through the control console to guide the slave robot to push, pull and rotate the catheter [11]. Clinical studies implied that compared to conventional endovascular surgery, the robotic endovascular technology is effective in reducing procedure time, improving stability and precision, a shorter learning curve and decreasing the dosage of radiation exposure for both the patient and physician [12-16].

1.2.1 Robotic Catheterization Platforms

Some commercial robotic catheter operating systems in Fig 1.1, all employed the master-slave control architecture, have demonstrated safety and efficacy in vascular and endovascular surgery [17]. The Niobe is a magnetically driven system that uses magnetic field generator located on either side of the patient, a specially designed catheter that copes with magnets in the catheter tip [18-19]. The active catheter is soft which potentially reduces the risk of cardiac perforation. The tip orientation and linear position of the catheter are controlled by joystick, roller wheels and mouse control [20]. The Amigo remote catheter system allows 3-DOF manipulation of standard EP catheter [14]. The master device mimics the standard catheter handle to remote control the catheter. It is also additionally equipped with features to prevent inadvertent catheter movement [21]. The Sensei robotic navigation system is a robotic arm attached to the patient’s table which allows 3-DOF manipulation of standard EP catheter by remotely using a 3-DOF joystick [22-23]. The driven components have also been adapted for navigation of endovascular catheters [24-25]. The CorPath vascular robotic system enables control of coronary guidewires, balloons, and stents during the percutaneous coronary intervention from x-ray radiation safety control console [26-28]. The

CorPath 200 is the only system that was evaluated in clinical studies. The system allows the operator to manipulate guidewires, balloon, and stents using a set of joysticks and touch screens while fluoroscopy provides visual feedback.

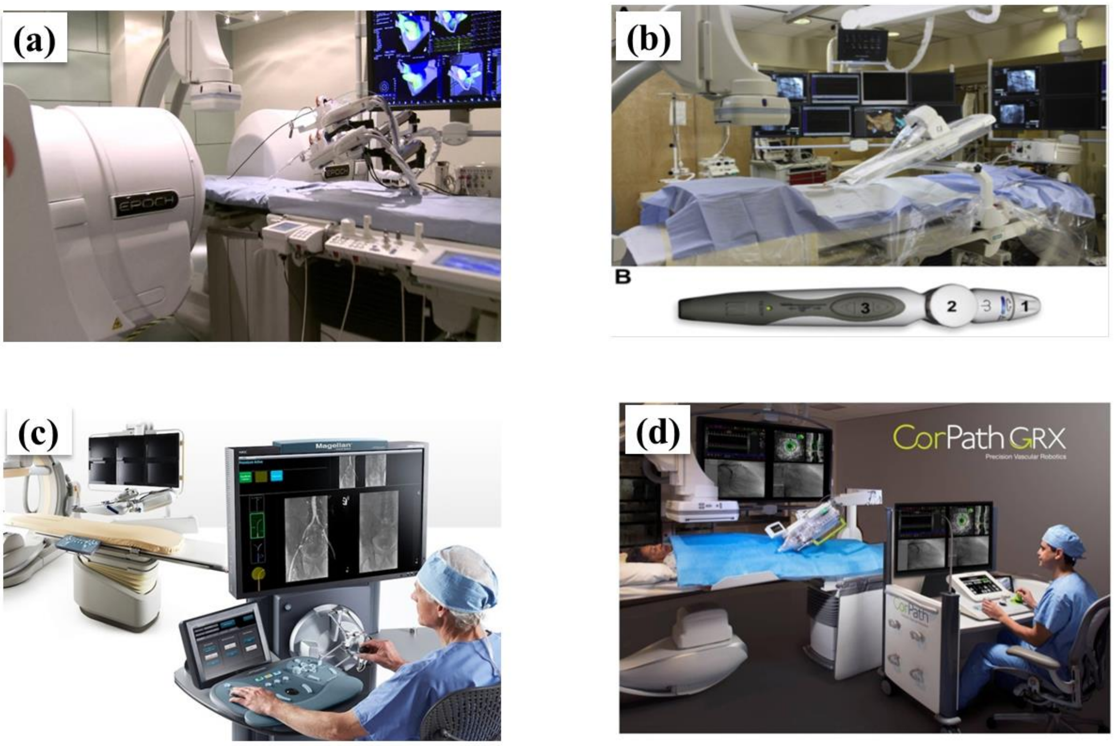


Figure 1.1(a) Niobe (Stereotaxis Inc., MO, USA) [18], (b) Amigo remote catheter system (Catheter Precision Inc., NJ, USA) [21], (c) Sensei robotic navigation system (Hansen Medical Inc., CA, USA) [22], (d) CorPath vascular robotic system (Corindus Vascular Robotic s, MA, USA) [26].

Robotic catheter operating systems have also been developed by several research groups. A compact telerobotic catheter navigation system was provided with the accuracy of 0.1mm and 7 deg over 100mm axial motion and 360 deg radial motion [29]. The system for endovascular teleoperated access was presented to manipulate any guide wire and catheter in the range of 0.014-0.13 inches. A 4-degree-of-freedom master-slave catheter and guidewire driving system was developed [30]. The system can enable the catheter and guidewire to be controlled independently in coaxial direction. In our previous studies, some novel remote-controlled vascular interventional robots were developed [31-39], which could operate the catheter in 2 DOFs and measure the proximal forces during the catheter insertion. Also, the VR-based haptic catheterization training system was developed for new surgeons [40-41].

1.2.2 Human-Centered Human-Machine Interaction

Human-machine interaction system supports bidirectional communications between human and interactive machine system [42]. Ergonomic consideration of the master device and incorporation of conventional catheterization skills into the system design is important in ensuring that the system is intuitive to use. For most existing robotic solutions, the master interface takes the shape of a joystick or a haptic device, therefore potentially altering the natural behavior and motion patterns of experienced operators [4]. This has driven research in recent years towards systems with more ergonomic master robots that exploit the natural manipulation skills of operators. Thakur et al. developed a novel remote catheter navigation system by using an input catheter placed in a radiation-safe location to control a second patient catheter [43]. Whilst this system has an intuitive input method, it only provides motion replication without providing force feedback to the operator. Another “hands-on” master-slave system of a similar architecture was developed that provides haptic feedback by estimating the motor current of slave catheter manipulator [44]. The system provides haptic feedback at the master device as vibrations to alert the operators. The Fig. 1.2 shows examples of systems whose master devices can be manipulated by the operators using conventional catheterization skills.

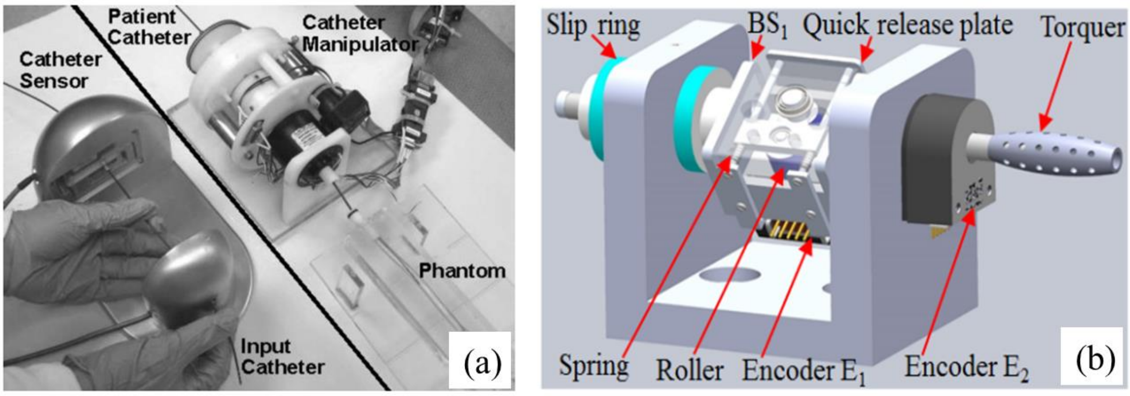


Figure 1.2 The systems developed by (a) Thakur et al. [43] and (b) Sankaran et al. [44], whose master devices can be manipulated by the operators using conventional catheterization skills.

1.3 Haptics for Robotic Endovascular Procedures

Incorporating haptic sensation to robotic systems for endovascular procedure is a quite essential [45]. The haptic feedback can be viewed as a way of communication between the human operator and tele-operation system [46]. Hence, the appropriate haptic based user interfaces must be developed.

1.3.1 Haptic User Interface

Haptic technology in teleoperated surgery is a promising research area. Some haptic devices have been developed, such as Sigma 7, HD2 and

Premium 3.0 master hand-controller, which have been applied in robot-assisted surgery system [47].The tactile sensation of the remote organ has been provided to the surgeon for teleoperated medical application [48]. Pacchierotti, C. et al. integrated haptic sensation (kinesthetic and vibratory information) in the master system for a teleoperated steering flexible needle surgery [49]. The target of these researchers was to get high quality of transparency and enhance the performance of robot-assisted surgery system by introducing haptic technology [50].

1.3.2 Haptic Feedback in Robotic Endovascular Procedures

To ensure surgery success, an ideal teleoperated surgery scenario is viewed as a physical extension of the human body. A high level of transparency is essential to an operator to make a right decision in human-centered teleoperation system. For example, the understanding of tissue characteristics is a determining factor for a successful teleoperated robot-assisted surgery [51].To this end, recreating haptic sensation in master side becomes urgently in robot-assisted surgery application. As Okamura, A.M., et al. pointed out that lacking haptic sensation was the main limitation in tele-surgery because the surgeon is physically separated far from the patient [45].

In the recent years, several research groups have proposed robotic catheter operating systems with incorporated haptic feedback, such as [30], [33], [36]. However, the master devices in these systems are all joysticks or commercial haptic devices. Therefore, the damping, inertia, and friction of electrical motors based haptic devices will significantly reduce the transparency of the system [52]. What's more, the medical professionals strongly rely on the sense of touch and their intuitive skills during endovascular surgery. However, the employment of these joysticks and haptic devices are potentially changing the natural gestures and behavior of experienced operators. So it is necessary to increase the natural haptic feedback in the master side by the catheter-based haptic interface.

1.4 Motivations and Objectives

1.4.1 Motivations

Currently, interventionalists overwhelmingly rely on 2-D visual feedback, as one of their dominant information sources, during robotic endovascular surgery. However, lack of the sensation of touch or haptic feedback from catheter-tissues contact to the operator is a drawback in current robot-assisted endovascular catheterization systems. The medical professionals strongly rely on the sense of touch and their intuitive skills during endovascular surgery. However, the employment of the robot-assisted endovascular catheterization system removes the catheter from the interventionalist’s hands, also eliminates the direct contact between the clinician and patient [10]. To this end, recreating effective haptic sensation by master haptic interface becomes urgently in the robot-assisted endovascular catheterization procedure [44].

The master haptic interface of designed robot-assisted endovascular catheterization system should contain two kinds of capability, measuring the axial and radial motions that applied by the interventionist, as well as recreating the effective haptic feedback to the interventionist. What is more, to get high quality of transparency and enhance the performance of surgery, the robot-assisted endovascular catheterization system should be provided with effective haptic feedback.

Inspired by such motivations, the development of a robot-assisted endovascular catheterization system should be in the following three aspects. Firstly, a magnetorheological (MR) fluids-based haptic interface for robot-assisted endovascular catheterization system was present. Secondly, in order to reflect the interactions between the catheter and vasculature, a dynamic model of catheter intervention was established. Finally, so as to assist the interventionalist indirectly control over the endovascular catheterization procedure, a haptic shared control strategy was implemented.

1.4.2 Objectives

In this thesis, the robot-assisted endovascular catheterization system has been proposed. The system can provide the operator with the ability to use their conventional bedside catheterization skills in robotic endovascular procedure. Meanwhile, the haptic feedback can be provided to the operator during the operation. In this design, the force model was presented to characterize the kinematics of the catheter intervention. Afterward, the 'pseudo collision' and 'real collision' were utilized to descript the catheter tip-vessel contact. The haptic shared control strategy has been utilized to assist the surgeon in decision-making and improving catheter interventional skills during teleoperated robot-assisted catheter interventional neurosurgery practice.

1.5 Thesis Outline

This thesis is organized as follows:

Chapter 2 deals with the interaction between the catheter and the vasculature. Specific catheter tip force sensor has been developed to measure the catheter tip-vessel force. The 'pseudo collision' and 'real collision' are utilized to descript the catheter tip-vessel collision.

In **chapter 3**, the haptic shared controlled architecture is proposed for robotic endovascular procedure. The catheter tip-vessel contact situations are adjusted to generate the haptic force.

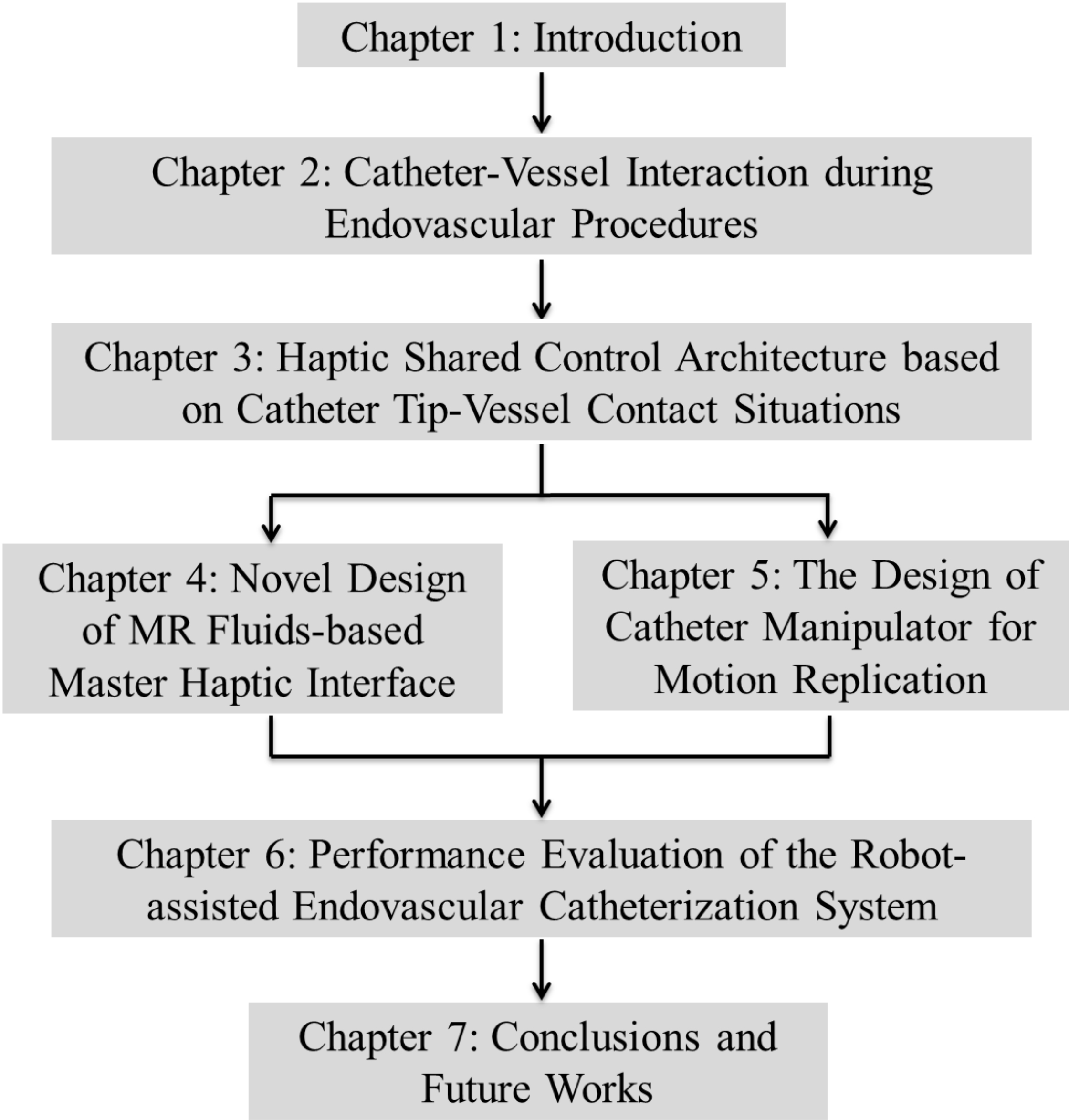
In **chapter 4,** the mechanical design of the MR fluids-based master haptic interface is described. The force model of haptic interface is presented. To achieve a quick response to haptic feedback, a novel hall sensor-based closed-loop control scheme was proposed for haptic force generation in the master haptic interface.

Chapter 5 introduces a catheter manipulator which integrated with a miniaturized proximal force sensing unit as a slave robot to manipulate the patient catheter and simultaneously measure the contact force between the catheter and the vasculature.

In **chapter 6**, teleoperation and haptic feedback control of the robot-assisted endovascular catheterization system are presented. Meanwhile, the performance evaluation of the robot-assisted endovascular catheterization system *in vitro* is carried out.

Chapter 7 summarizes key findings and contributions of the thesis and lays out the future works of robot-assisted endovascular technology.

1.6 Structure of the Thesis



Chapter 2 Catheter-Vessel Interaction during Endovascular Procedures

In this chapter, the interaction force between the catheter and the vascular system has been analyzed. The viscous force and contact friction force are hardly be measured and estimated in real time. However, the total interaction force between the catheter and the vasculature can be measured by the proximal force sensing unit of catheter manipulator in robotic endovascular procedure. This force sensing unit will be described in chapter 5 in detail. In order to discrimination the collisions of catheter tip-vessel, the 'pseudo collision' and 'real collision' theory is carried out. To measure the collision force, a catheter tip force sensor has been proposed and calibrated. The understanding of those interaction forces may help in establishing the force or haptic feedback in robotic endovascular procedures by master haptic interface.

Chapter 3 Haptic Shared Control Architecture based on Catheter Tip-Vessel Contact Situations

In teleoperated surgery, the impedance information (force and velocity) is bilateral exchanged between the local system and the remote system. Therefore, the success of teleoperated surgery is depended on the operator's cognition ability of transmitted haptic impedance and decision-making when he/she operates the haptic interface in the master site. The master system contains the human operator, haptic interface, and master controller. It can be viewed as human-machine interaction (HMI) system.

The haptic shared control strategy was proposed. Three force level thresholds were utilized to represent interaction situations between the catheter tip and blood vessel wall, which were used to alert the operators that the 'pseudo collision' or 'real collision' happened. The experimental results indicate that haptic guidance has the ability to assist operators in decision-making to change the manipulation gestures to decrease the contact force.

Chapter 4 Novel Design of MR Fluids-based Master Haptic Interface

This chapter proposes an MR fluids-based master haptic interface for robot-assisted endovascular catheterization procedure. The distinctive feature of the master haptic interface is that the MR fluids-based device was utilized, and this design allowed the input catheter as an operating tool not only can transmit the operating commands but also can reflect the haptic feedback to the operator. The commercially available joysticks or haptic interface device like Omega were as the master devices, which removed the catheter from the physicians' hands, thus their conventional bedside technique skills cannot be used during the robotic endovascular procedures. Experimental results showed that the mean accuracy of axial motion is 0.04 mm (precision, ±0.05 mm) for 100 mm length of catheter insertion. And the considerable range of generated passive resistance force is from 28 mN to 1206 mN.

In designing the closed-loop control strategy for the haptic forces generation, the output resistance forces were regulated using the magnetic field measurements that acquired by embedded hall sensors. By this method, the effect of hysteresis phenomenon can be eliminated, and the maximum setup and elimination time of output resistance force were below 220 ms. However, the perceived resistance force of catheter insertion impacts by the manipulation speed of input catheter, as shown in Fig. 4.19.

The biggest difference is 41 mN when the applied magnetic field is at 240 mT and the two insertion speeds are 2 mm/s and 200 mm/s. This kind of influence can hardly be removed, hence in our haptic feedback design, four different magnetic fields, the interval is 60 mT, were applied to generate the resistance forces to represent interaction situations between the catheter and the vasculature which the differences of adjacent force thresholds can be recognized.

Chapter 5 The Design of Catheter Manipulator for Motion Replication

This chapter proposes a catheter manipulator to actuate the patient catheter in transitional ways, push, pull, and rotate, as well as measure the contact force between the catheter and vascular system. The robot cannot enable the translation and rotation motion simultaneously, since that is according to the conventional catheterization procedures. The simplicity of an experiment was performed to evaluate the accuracy of the catheter manipulator. The average accuracy of catheter manipulator was better than 1 mm and 2 deg in the axial and radial direction, respectively. Some remote catheter navigation systems are now commercially available. Two robot-assisted percutaneous coronary intervention systems (CorPath 200 and CorPath GRS, Corindus Vascular Robotics) are currently available in medical applications [5]. For CorPath GRS, the guide catheter liner position error is below 2.5 mm, and the rotational position accuracy (guidewire only) is 3 deg using touch-screen keys [100]. For Amigo remote catheter system (Catheter Precision Inc., NJ, USA) [101], the linear and rotation resolution of the catheter manipulation is 1.6 mm and 1.1 degrees, respectively.

In order to provide the haptic feedback to surgeons, a novel miniaturized proximal sensing mechanism is proposed as a part of catheter manipulator to measure the contact forces between the catheter and vasculature during endovascular procedures. The measured force data represents two main components: collision force and friction force. Collision force is developed at the catheter tip due to the contact with the obstacle (blood vessel wall or a plaque) which transmitted via the catheter to the proximal force sensor. The friction force is developed between the catheter surface and inner blood vessel wall.

Chapter 6 Performance Evaluation of the Robot-assisted Endovascular Catheterization System

In this chapter, the robot-assisted endovascular catheterization system is presented that provided the interventionalist with the ability to use their conventional bedside skills in robot-assisted endovascular catheterization process. The haptic shared control strategy has been designed for haptic feedback.

The simplicity of an experiment was performed to evaluate the response time between sensed and replicated motion is an important issue. The lag with the designed system was less than 160 ms. It could be attributed to two reasons: one is attributed to the inherent communication lag between the master haptic interface and catheter manipulator. Another is that the grasper and the chuck of catheter manipulator need enough motion time to clamp and release the catheter, also the increasing the number of directional changes may result in increasing the motion lag. From Fig. 6.3, the mean value of motion lag in the axial direction was about 102 ms. In comparison, in the radial direction lag times as much as 158 ms were measured. That may be because, in the axial direction, the changes in the position are easily perceived, while changes in the radial orientation of the catheter manipulator are actuated by belt-drive transmission system which the slips may cause the latency. Although these issues always existed, the caused errors can be partly offset in practice by the operators, who will use fluoroscopic imaging as position feedback of the patient catheter.

Based on designed haptic guidance, from the Table II, the mean of the maximum contact force was decreased after provided haptic guidance to operators. The experimental results indicate that haptic guidance has the ability to assist operators in decision-making to change the manipulation gestures to decrease the resistance force when it exceeds the thresholds. *In vitro* evaluation, we did not set the “stop threshold”, which can be used to control the automatic stop of the catheter manipulator. However for the safety of surgery, when the measured contact force exceeds the threshold safety value, all catheter movements of catheter manipulator should be stopped immediately. Moreover, the catheter manipulator must be separated with the patient catheter freely, and the physicians could use their conventional skills to go on the surgery. For the further real application, the “stop threshold” should be taken into consideration, and also the structure of the catheter manipulator should be further optimized.

The designed haptic guidance scheme had substantially shortened the procedure time, (in Fig. 6.6) and decreased the resistance forces (Table 6.1) compared to no haptic guidance during the operation. This means that the operation skills were potentially improved, such benefit of haptic guidance in task implementation was reported in many other studies [49], [69], [70]. Also, the reduction in procedure time could potentially translate into reduced human cognitive workload during the operation. The reduced magnitude and time impact of the contact forces may indicate that the safety of the surgery will be increased. From Fig. 6.7, the significant improvements in the decreasing the contact forces with the haptic guidance by subject 1 was found. Nonetheless, due to the time consumption of setup and elimination of required magnetic field, the inevitable slight time lag was within 300 ms, which as the maximum tolerable image-display lag time was to ensure safe remote surgical manipulation in the clinical setting [102].

Chapter 7 Conclusions and Future Works

7.1 Contributions and Achievements of this Thesis

In recent two decades, the development of robot-assisted endovascular catheterization system was motivated by the desire to reduce fluoroscopy time, radiation dosage to surgeon and patient in addition to reduction of surgeon fatigue, and improvement of position accuracy of catheter. Unlike the conventional bedside technique, the robot-assisted endovascular catheterization system allows the interventionalist to offer traditional axial and radial action by master robot placed in a remote location through the control console to guide the slave robot to insert, retract and rotate the catheter. Currently, interventionalists overwhelmingly rely on 2-D visual feedback, as one of their dominant information sources, during robotic endovascular surgery. However, lack of the sensation of touch or haptic feedback from catheter-tissues contact to the operator is a drawback in current robot-assisted endovascular catheterization systems. The medical professionals strongly rely on the sense of touch and their intuitive skills during endovascular surgery. However, the employment of the robot-assisted endovascular catheterization system removes the catheter from the interventionalist's hands. For most existing robotic solutions, the master interface takes the shape of a joystick or a haptic device, therefore potentially altering the natural behavior and motion patterns of experienced operators. To this end, recreating effective haptic sensation by master haptic interface becomes urgently in the robot-assisted endovascular catheterization procedure.

To address these issues, the study presented in this thesis proposes the robot-assisted endovascular catheterization system which can provide the operator with the ability to use their conventional bedside skills in robot-assisted endovascular catheterization procedure. Meanwhile, the haptic feedback can be provided to the operator during the operation. In this design, the force model was presented to characterize the kinematics of the catheter intervention. The haptic shared control strategy has been utilized to assist the surgeon in decision-making and improving catheter interventional skills during teleoperated robot-assisted catheter interventional neurosurgery practice. Furthermore, a novel robot-assisted endovascular catheterization system is presented. The MR fluids-based master haptic interface has been designed and fabricated. The force model of haptic interface is presented. To achieve a quick response to haptic feedback, a novel hall sensor-based closed-loop control scheme was proposed. The catheter manipulator which integrated with a miniaturized proximal force sensing unit was as a slave robot to navigate the patient catheter and simultaneously measure the contact force between the catheter and the vasculature. The catheter manipulator was evaluated for precision positioning. The time lag from the sensed motion to replicated motion is tested. To verify the efficacy of the proposed haptic guidance method, the evaluation experiments *in vitro* are carried out. The results demonstrate that the proposed system has the ability to enable decreasing the contact forces between the catheter and vasculature.

The achievements of this thesis are as follows:

(1) The analysis of catheter intervention in catheterization procedure was carried out. The 'pseudo collision' and 'real collision' are utilized to descript the catheter tip-vessel contact. A catheter tip force sensor was proposed and calibrated.

(2) The haptic shared control strategy has been utilized to assist the surgeon in decision-making and improving catheter interventional skills during teleoperated robot-assisted catheter interventional neurosurgery practice.

(3) Implement the force closed-loop control in designed MR fluids-based master haptic interface. Provide a miniaturized proximal force sensing unit in catheter manipulator.

(4) The designed system can provide the stable haptic guidance to the operator. The haptic guidance was a benefit for providing natural haptic sensation and reducing the human cognitive workload as well as keeping the safety of surgery.

7.2 Future Works

For widespread use of robot-assisted endovascular catheterization systems, the development of ergonomic robotic platforms that maintain the natural skill of the operator is a potential area for future research.

Publication List

International Journals Papers

1. **Yu Song**, Shuxiang Guo, Xuanchun Yin, Linshuai Zhang, Hideyuki Hirata, Hidenori Ishihara, Takashi Tamiya, “Performance evaluation of a robot-assisted catheter operating system with haptic feedback”, Biomedical Microdevices, In press, DOI: 10.1007/s10544-018-0294-4, June, 2018, Impact Factor (IF): 2.062.

2. **Yu Song**, Shuxiang Guo, Xuanchun Yin, Linshuai Zhang, Yu Wang, Hideyuki Hirata and Hidenori Ishihara, “Design and Performance Evaluation of a Haptic Interface based on MR Fluids for Endovascular Tele-surgery”, Microsystem Technologies, Vol.24, No.2, pp.909-918, 2018. Impact Factor (IF): 1.195.

International Conference Papers

1. **Yu Song**, Shuxiang Guo, Linshuai Zhang, Miao Yu, “Haptic Feedback in Robot-assisted Endovascular Catheterization”, Proceedings of 2017 IEEE International Conference on Mechatronics and Automation, pp. 404-409, 2017.

2. **Yu Song**, Shuxiang Guo, Linshuai Zhang, Xuanchun Yin, “MR Fluid Interface of Endovascular Catheterization Based on Haptic Sensation”, Proceedings of 2016 International Conference on Mechatronics and

Automation, pp. 542-546, 2016.

3. **Yu Song**, Shuxiang Guo, Linshuai Zhang, "An Ergonomic Master Haptic Interface for the Robot-assisted Endovascular Catheterization System", Proceedings of 2018 IEEE International Conference on Mechatronics and Automation, In press, May, 2018.

4. Shuxiang Guo, Miao Yu, **Yu Song**, Linshuai Zhang, "The Virtual Reality Simulator-based Catheter Training System with Haptic Feedback", Proceedings of 2017 IEEE International Conference on Mechatronics and Automation, pp. 922-926, 2017.

Biographic Sketch

Yu Song received M.S. degree in control engineering from Tianjin University of Technology, Tianjin, China, in 2015. He is currently working toward the Ph.D. degree in Intelligent Mechanical Systems Engineering at the Kagawa University, Japan. His current research interests include the areas of minimally invasive surgery, haptics, and medical robot.

He has published over 6 refereed journal and conference papers in recent three years.