THE THESIS OF DOCTOR OF PHILOSOPHY

Study on a Novel Virtual Reality Interventional Training System for Robot-assisted Interventional Surgery

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Abstract

Cardiovascular diseases are the leading cause of death worldwide except Africa. Vascular interventional surgeries (VIS) have become common alternatives because it has some advantages such as short recovery time, a small incision to the healthy tissue and little postoperative pain. However, prolonged exposure to X-ray radiation during surgery will cause a serious impact for the surgeons' health. The endovascular robotic systems have been developed to release surgeon from the risks of radiation and heavy radiation-shielded garments. This system allows surgeons to manipulate catheter via master side over long distance. Compared with traditional VIS, robot-assisted interventional surgery requires surgeons to be highly skilled at manipulating vascular interventional surgical robot, and the use of robots for surgery has changed surgeons' surgical habits. Surgeons need to be trained at endovascular robotic system to adapt to robot-assisted interventional surgery.

Traditional training methods, including using live animals, human cadavers and vascular phantom, have many limitations such as expensive, risky and limited morphological models. Virtual reality (VR) interventional training systems for robot-assisted interventional surgical training have many advantages over traditional training methods. Computer-based simulation of catheterization procedures provides a

versatile solution and can virtually be reused infinite times on both common and rare cases. Moreover, patient-specific data can be quickly adopted to regenerate the virtual environment, which provides tools for surgeons to plan or rehearse preoperatively to evaluate and optimize the tentative surgical procedure. However, the interventional simulation is still not realistic enough compared with traditional training methods.

In this thesis, we developed a novel virtual reality interventional training system for robot-assisted interventional surgery. This system includes two parts: the master side and the VR simulator. For master side, we developed a novel haptic force interface to realize haptic feedback. Moreover, a collision protection function with a proximal-force-based collision detection algorithm was proposed to improve surgical safety. In case of no collision, transparency of the teleoperated system is realized; in case of collision, the provided haptic force will be amplified. For VR simulator, we proposed a novel method to solve catheterization modeling during the interventional simulation. Our method discretizes the catheter by the collision points. The catheter between two adjacent collision points is treated as thin torsion-free elastic rods. The deformation of the rod is mainly affected by the force applied at the collision points. Meanwhile, the virtual contact force is determined by the collision points. This simplification makes the model more stable and reduces the computational complexity, and the behavior of the surgical tools can be approximated. Therefore, we realized the catheter interaction simulation

and virtual force feedback for the proposed VR interventional training system.

From the experimental studies, the haptic force interface can provide precise force to the operator, and the motion accuracy is enough for the robot-assisted interventional surgery. The proposed collision detection algorithm can detect the collision in different surgical stages. The proposed method for simulating catheter interaction is enough to achieve satisfactory outcomes and the average running time for solving the deformation between two collision points satisfies the requirement of interventional simulation. The developed VR interventional training system has potential to be used in robot-assisted interventional surgical training.

Contents

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strong financial guarantee and spiritual support. Without them, I will fall down with countless setbacks.

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.

Chapter 1 Introduction

1.1 Background

Cardiovascular diseases (CVD), including the thrombus, atherosclerosis, and aneurisms, are the leading cause of death worldwide except Africa [1]. Vascular interventional surgeries (as shown in Figure 1-1) have become common alternatives because it has some advantages such as short recovery time, a small incision to the healthy tissue, good surgical outcomes, and little postoperative pain [2]. However, prolonged exposure to X-ray radiation during surgery will cause a serious impact for the interventionalists' health [3]. Fortunately, the development of endovascular robotic systems has the potential to release surgeon from the risks of radiation and heavy radiation-shielded garments. Endovascular robotic systems allow surgeons to manipulate catheter via master side over long distance. Moreover, endovascular robotic systems have higher operating accuracy, and it can assist surgeon to perform more sophisticated surgical operation [4].

Robot-assisted interventional surgery requires surgeons to be highly skilled at manipulating vascular interventional surgical robot. Compared with traditional VIS, the robotic system has changed surgeons' surgical habits [7]. As a result, surgeons need to be trained at endovascular robotic system to adapt to robot-assisted interventional surgery. In addition, traditional interventional training methods, including using live animals, human cadavers and vascular phantom (as shown in Figure 1-2), have many limitations such as expensive, risky and limited morphological models [8]. Virtual reality interventional training systems were developed as a means of improving training and reducing the costs of education, as shown in Figure 1-3. Computer-based simulation of catheterization procedures provides a versatile solution and can virtually be reused infinite times on both common and rare cases [9]. Moreover, patient-specific data can be quickly adopted to regenerate the virtual environment, which provides tools for surgeons to plan or rehearse preoperatively to evaluate and optimize the tentative surgical procedure.

Although the VR interventional training systems have many advantages, there still hard to be used in robot-assisted interventional surgeries. One of the major problems is that most of existing VR interventional training systems is used for traditional surgeries, which are not suitable for robot-assisted interventional surgeries. Therefore, it is necessary to develop a VR interventional training system based on the endovascular robotic system. Combining the endovascular robotic system and VR simulator can adapt the surgeon to the robot-assisted interventional surgeries and improve their surgical skills.

1.2 Endovascular robotic system

Up to now, numerous companies and research groups have developed endovascular robotic systems like CorPath robotic system, Amigo robotic system, Niobe magnetic navigation system and Magellan/Sensei robot system [16]-[19], as shown in Figure 1-4. Although these systems used in VIS have proven to have notable advantage, such as reduced exposure [20]-[21] to radiation for intervening physicians and improved operation accuracy [22]-[23], the robotic systems developed so far have failed to provide an intuitive user interface which can take full advantage of natural manipulation skill for surgeons. One of the major reasons is that current endovascular robotic systems lack high-precision haptic force feedback. Inaccurate force feedback in the robot-assisted interventional surgeries affects physicians' judgment and increases the risk of surgery. In addition, studies on contact force estimation between surgical tools and vessel are limited and it do not provide an effective way to detect catheter-vessel collision. The excessive contact force may make the catheter tip puncture the blood vessel wall and increase risk of procedure. Furthermore, the interfaces that are used to control robot in current robotic systems are manipulator, joystick, mouse and touch screen. These interfaces do not conform to the natural operating habits of surgeons. As a result, the intervening physicians need to learn new skills to use the robotic system for performing procedures [24].

Considering the importance of haptic force interface, many research groups have adopted various ways to realize haptic force feedback. Dagnino et al [25] used the voice coil motor to generate the force, as shown in Figure 1-5 (a). This kind of motor simulates nature permits a quick translation of the contact forces to the surgeon. Yin et al [26] developed a passive haptic force interface using magneto-rheological fluids (MRF), as shown in Figure 1-5 (b). This interface exhibits high precision in the control of output of force and torque. The purpose of current research is to build the relationship between the force and force generator (motors or smart materials) previously and use voltage or current to control the force generator. However, current haptic force interfaces lack of way to measure the provided haptic force during surgery, which leads to potential errors in different surgical environment. Although effort has been put into the development of haptic force interface over many years, a satisfactory artificial haptic force interface that can provide high-precision force feedback has not yet been realized, and in turn limits progress in fields such as robotics and VIS [27].

With the aim of improving safety, the operator avoids applying excessive force on surgical tools to reduce the damage to the blood vessel caused by collision. Current research tends to use sensors or special surgical environment to detect collisions. Payne et al [28] used strain measurement sensor mounted on the catheter tips, as shown in Figure1-6 (a). This sensor converts the deflection of the catheter into force values.

However, due to the large size of this kind of sensor, it is hard to be used in VIS. Fiber-optic pressure sensors (as shown in Figure1-6 (b)) have potential to be used in interventional surgeries [29], but it is limited by some complex vasculature such as cerebrovascular. Part of the cerebrovascular has great bending angle and it will impact the accuracy of the fiber-optic pressure sensors. Moreover, Guo et al [30] presented a visual-based method to measure the contact force between the catheter tip and vessel, as shown in Figure1-6 (c). With the 2-D ultrasound image and tracking a passive marker attached to the catheter tip, this method can estimate the contact force via measuring the length variation of the marker. However, the methods based on special surgical environment, such as magnetic field or ultrasound, are difficult to be used in all procedures [31].

1.3 VR simulator

The VR simulator is used to construct the virtual interventional environment. In the context of computer-based simulation of catheterization procedure, the virtual interventional environment can be established by patient-specific data. This makes the interventional training no longer limited to a few vasculature models, while reducing training costs. For interventional simulation, one of the most challenging works is to faithfully reproduce the behaviors of surgical tools, including the deformation and virtual contact force.

To predict complex behaviors of surgical tools, several approaches have been proposed [32]. Duriez et al. proposed an incremental finite element method (FEM) to simulate the catheter navigation [33]. The vessel geometry puts strict position constraints upon the catheter. Considering the non-linearities arising from large catheter deformation, the incremental FEM method exists a cumulative error on the catheter shape. Li et al. proposed an improved FEM approach based on the principle of minimal total potential energy [34]-[35]. Alderliesten et al. modeled the device as linked rigid bodies based on multi-body dynamics. With complex bending energy and material properties incorporated, this method achieved high accuracy along with a heavy computational workload, especially as the number of connected joints increased [36]-[37]. Mass-spring catheter models have been proposed as well [38]-[39]. These models are very efficient but cannot ensure to preserve the overall catheter length, since this causes these equations to become numerically stiff and hard to compute. Alderliesten et al. designed a method relying on a quasi-static minimum energy principle [40]. The method departs from the observation that dynamic effects can often be ignored as motions take place in a heavily dampened environment and are generally fairly slow. The argument is that the guidewire (and, by extension, the catheter) thus has the time to relax and take on a configuration where the overall energy of the system, consisting of the potential energy due to deformation of the catheter and the surrounding vessel structure, is minimal. This method has been extensively validated on guidewire motion but is here expanded to predict and control catheter motion [41].

1.4 Thesis Objectives

In this thesis, a novel VR interventional training system was developed for robot-assisted interventional surgeries. This system is an extension of the endovascular robotic system. Because the master side of this system can be used for both the endovascular robotic system and the VR interventional training system, the proposed system improves training and reduces the cost of education. To achieve the overall objective, this thesis has the following set of sub-objectives:

(1) A novel haptic force interface was proposed. The closed loop system based on force signal can ensure the accuracy of force feedback.

(2) A collision protection function with a proximal-force-based collision detection algorithm was proposed to improve surgical safety.

(3) An improved centerline extraction method was proposed to extract the radius and centerline of vascular mesh.

(4) A novel catheterization model was used in VR simulator to simulate the dynamic behavior of catheter.

(5) A novel VR interventional training system was developed to improve surgeon's surgical skills. The haptic force interface can be used for both endovascular robotic systems and VR

interventional training systems. The VR simulator can simulate the catheter shape and provide virtual force feedback.

1.5 Thesis Overview

In this thesis, the developed VR interventional training system including two parts: the master side and the VR simulator. The master side is introduced at chapter 2, 3. Chapter 4, 5 are for the VR simulator. The whole VR interventional training system is illustrated at chapter 6. The details are as follow:

In chapter 2, a novel master side is developed. The master side includes measurement device, haptic force feedback and processing core.

In chapter 3, a z-score based collision protection method is proposed.

In chapter 4, an improved centerline extraction method is proposed. This method can get centerline and radius from the vascular mesh.

In chapter 5, a novel catheter interaction simulation method is proposed.

In chapter 6, a virtual reality interventional training system is proposed.

The chapter 7 as the last one includes the conclusions and future works.

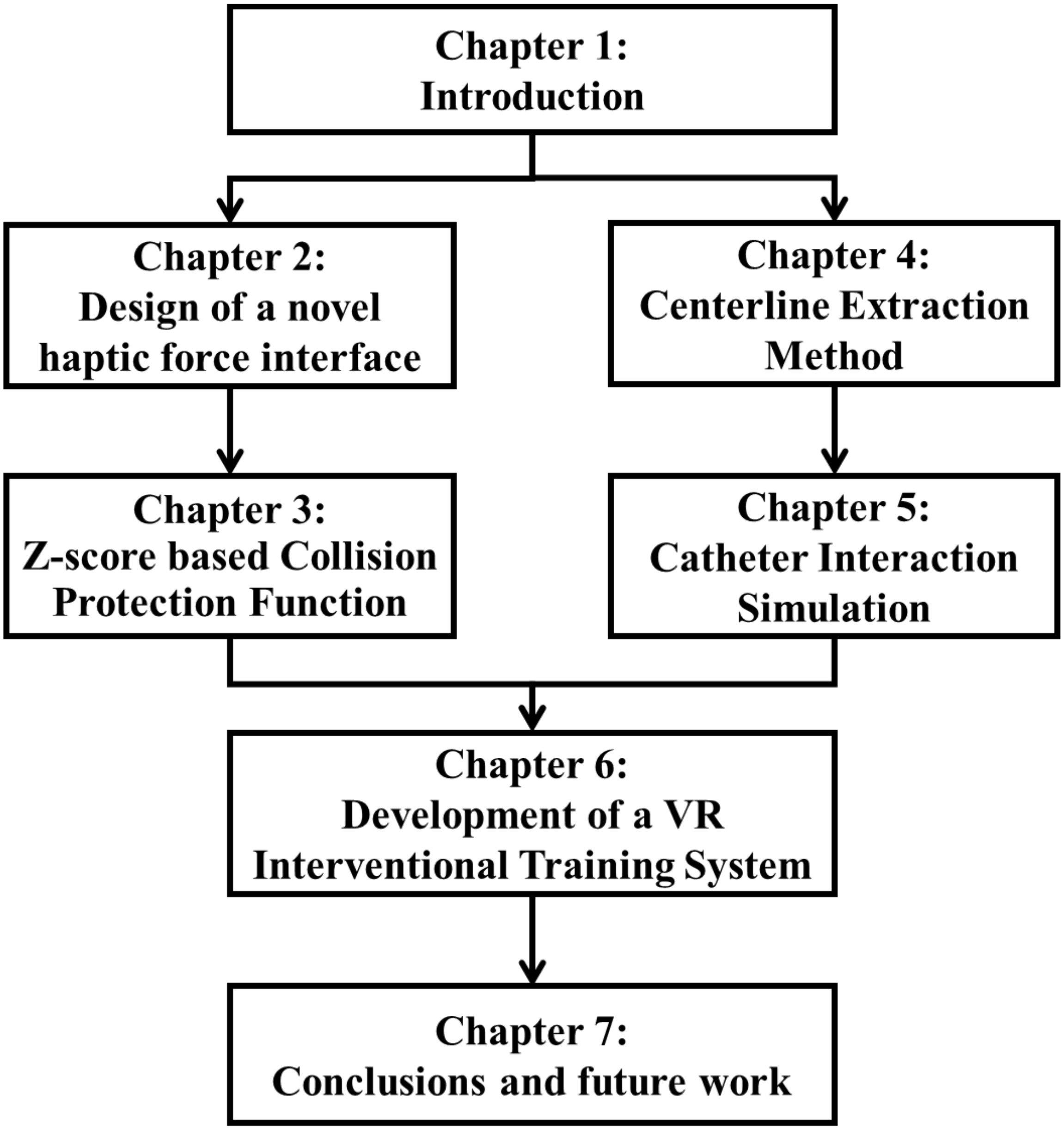

Figure 1-7 Structure of the thesis

Chapter 2

Design of the master side

The design goal of the master side is to achieve kinesthetic feedback between the environment and the human operator. In other words, the operator feels as if the task object were being handled directly [42]. However, the operator may sometimes get tired of holding a constant weight and calls for a system with continuous variation of the force feedback ratio to reduce fatigue and improve precision, since this brings out the necessity of designing an adjustable system [43].

In the context of robot-assisted interventional surgery, the surgeon manipulates the catheter by operating the master side and senses the haptic force provided by the haptic force interface. Therefore, the master side needs to implement two basic functions: measuring the motion of operator (measurement device is called here) and providing the haptic force to operator (haptic force interface is called here). The motion and force signal are processed at the processing core. The overview of the endovascular robotic system is shown in Figure 2-1. The model of the developed master side is shown in Figure 2-2 (a), and the design parameters are shown in Table 2-1.

In the robot-assisted interventional surgery, the surgeon's action is measured in master side and transmitted to the slave side to navigate the patient catheter. The motion deviations in master side may cause the surgeon manipulating catheter inaccurately and improve the surgical risk. Previous research shows that the motion accuracy, which is showed in accuracy evaluation, is enough for the robot-assisted interventional surgery [46]. On the other hand, the perceptual resolution in force discrimination, as measured by the just noticeable difference (JND), is 7-10% over a range of 0.5-200N [47]. Considering the results of the transparency evaluation result, the proposed spring-based haptic force interface can accurately provide the haptic force.

In addition, transmission delay affects the ability of human operators to assess catheter status of the remote environment. Fu et al [48] proposed a unified framework for human haptic perception with delay force feedback. This framework can accurately predict all effects caused by time delay. Nisky et al [49] studied the effect of delay on perception in a simulated needle insertion task. They found that using appropriately choosing a position gain and reciprocal force gain of a teleoperation channel can cancel the effect of delay. In further research, delay compensation control method should be introduced in the control strategy to improve the performance of the designed system.

In this chapter, a novel master side was proposed. Since the closed loop system in the presented haptic force interface is based on force signals, the accuracy of provided haptic force feedback is confirmed. The haptic force is generated by the spring-based force generator. Due to the elasticity of the blood vessel, the spring is more suitable to simulate the contact force between the surgical tools and blood vessel wall. A rigid metal rod is used to control the robot. As an alternative to a catheter, it can keep the natural manipulation skill of surgeon and transmit the haptic force to the operator effectively. From the experimental studies, the haptic force interface can provide precise force to the operator, and the motion accuracy is enough for the robot-assisted interventional surgery.

Chapter 3

Z-score based collision protection function

During classical interventional surgeries, surgeons often use their hands to estimate how much force should be applied so that the blood vessel wall is not damaged. When an abnormal proximal force is felt, the surgeon must retreat or rotate the catheter to change the form (direction or shape) of the catheter. But from a human factors point of view, surgeons may sometimes get tired for a long surgery, and ignore some collision information to reduce fatigue and improve precision.

In robot-assisted interventional surgeries, one of the benefits is that endovascular robotic system has the high accuracy of force sensing and the accurate does not decrease during the procedure. Current research can detect the collision between catheter tip and blood vessel wall by using sensors or special surgical environment. However, this technique still hard to be used in real procedure.

In this chapter, we proposed a novel collision protection function. The collision detection algorithm is based on force change rate detection, and it aim to imitate the surgeon’s feeling of collision. The protection function will warn the operator when a collision is detected during surgery.

In conventional VIS, the judgement of catheter-vessel collision relies on surgeons' experience. Our goal is using collision detection algorithm to simulate this experience. Due to complex of vascular system, change in proximal force caused by catheter-vessel collision is different in various stages of surgery. Although the proposed method can change the safety range during surgery, due to conflict between stability and adaptability, this change is still not enough for a long surgery. The solution is to separate the safety range from collision detection algorithm and keeps stability of collision detection algorithm. In addition, the parameters of the developed algorithm need to be adjusted according to the different surgical environment. In future research, an adaptive algorithm should be developed to adjust the parameters for different situation.

However, increasing the feedback force when the algorithm detects a collision will impact the transparency of the interface. As a result, the operator needs to be trained before using the system. We can also change the force scaling parameter α or use another way to reminder the operator, such as visual or shock, to reduce the impact on operators.

In this chapter, a collision protection function was developed to assist surgeon to avoid catheter-tissue collision. If the algorithm detects a collision, the haptic force interface will provide a warning force to notify the operator, and the operator will change operation (retraction or rotation) to reduce damage to the vessel. From the experimental studies, the proposed collision detection algorithm can detect the collision in different surgical stages. Since no additional sensors or special environment are needed, the proposed collision detection algorithm can be easily applied to other endovascular robotic systems without significant modification.

Chapter 4

Centerline extraction method

Vascular interventional surgery requires surgeon to be highly skilled at manipulating the surgical tools to avoid damaging vasculature system. Virtual reality (VR) interventional training systems were developed to reduce the training cost and improve training. For virtual interventional radiology, centerline of the vasculature is often used to reconstruct vasculature and detect the contact between surgical tools and blood vessel wall. In addition, vascular centerline is an important cue for surgeon. During virtual interventional training task, the VR simulator encourage operators to move both the catheter and guidewire along the centerline to reduce collision.

However, centerline extraction of vasculature is a complex task because the vasculature possesses complicated geometry and topology, such as hemangioma and capillaries. Moreover, original vasculature data is usually extracted from computed tomography (CT) or magnetic resonance angiography images. The extracted data may exist artifacts, such as staircases and noise, and it also hinder the centerline extraction [56]. In virtual interventional radiology, the centerline is closely related to curve skeletons. However, due to the specific shape of vasculature mesh, it is not a same problem for centerline/curve-define extraction from 3D shapes. From the perspective of the type of input model, the centerline extraction methods mainly include volume-based method, surface mesh-based method and point cloud-based method.

Volume-based method compute the minimum distance to boundary for internal voxels to get a distance field and use rigid voxels as candidate voxels for centerline construction. Blum's medial axis and its variants are designed to obtain centerline by capturing reflectional symmetries in a shape [57]. The medial axis of a 3D model is generally a non-manifold containing 2D sheets that are hard to store and manipulate. A 1D centerline is more useful in practice. Most commercial software use volume data to extract the vasculature centerlines, such as MeVisLab and MedCAD [58] [59]. However, when volume data is lacking, the software does not work very well. Surface mesh-based methods have a wider range of adaptability. Wang and Lee used iterative least squares optimization method that shrinks models and applied the thinning algorithm to extract 1D skeletons [60]. Au et al used implicit Laplacian smoothing with global position constraints to contract the mesh [61]. The contracted mesh is then converted into the curve skeleton while preserving the shape of the contracted mesh and the original topology. These methods aim to deal a series of shapes for a wider applicability. However, these methods are complicated and hard to be performed on vasculature mesh. Point cloud-based method can usually produce quality results for simple objects that are represented by point cloud. Sharf et al. proposed a method to compute a curve skeleton by a deformable blob grown form the “inside” of input cloud [62], and Tagliasacchi et al. achieve the extraction through a generalized rotational symmetry axis-based method [63]. These two methods are based on point cloud and can run under moderate amounts of missing data. Huang et al. propose a medial curve skeleton of a point cloud [64]. However, this method does not distinguish points from different structures. Therefore, it produces curve skeletons with incorrect topology for complex shapes. For the different type of shapes, it can be converted to each other, and then use the corresponding method to find the centerline. Unfortunately, this is prone to error in constructing an object's internal geometry and topology [65].

In this chapter, an improved centerline extraction method suitable for mesh representation of vasculature was proposed. The method is based on the assumption that the vasculature system is form by a set of continuous cylindrical shapes. This obtains an effective way to solve the vasculature centerline extraction problem. The centerline is formed by center point of the cylindrical shapes and the centerline is satisfied rotational symmetry. The benefit of rotational symmetry is that it can compensate for the missing data for vasculature mesh. In order to improve the operating efficiency, we proposed pre-processing strategy to merge duplicate vertices. Meanwhile, the plane normal vectors are converted to vertex normal vectors. In addition, the center point of end surface in vasculature mesh is removed to improve the stability. Using the pre-processing strategy, the vasculature mesh is turned to vasculature point cloud while preserving the integrity of the vasculature. The experiment show that the improved centerline extraction method is sufficient to extract a complete centerline, and the pre-processing can effectively reduce the number of vertices.

Chapter 5

Catheter interaction simulation

Human-machine interaction in virtual interventional simulation includes visual and haptic. In the context of VIS, the proximal force is the resultant force generated by the interaction between the surgical tools and the blood vessel [69]. For the VR interventional simulation, friction and collision were incorporated as the most influential forces applied to the instrument during the propagation within a vascular system [70]. The calculation of virtual contact force relies on the detection of the collision between virtual surgical tools and vasculature mesh, and simulation of the deformation of the virtual surgical tools is the key to obtain collision information.

In practice, the guidewire and the catheter are always coaxial in the course of the procedures. To avoid the complex interaction between the guidewire and the catheter, we use a single physical model (here is the catheter model) to instead of catheter-guidewire combination. Moreover, because the propagation of twisting waves is much faster than bending waves in elastic rods, the catheters and guidewires can be treated as the material frame quasi-statically [71]. Therefore, we consider the catheter model as thin torsion-free elastic rod.

In this chapter, a novel method is proposed to simulate the behaviors of surgical tools, including the deformation and virtual contact force. Our method discretizes the catheter by the collision points. For each part between two adjacent collision points, the catheter is treated as a thin torsion-free elastic rod. Therefore, the catheter model is as a structure composed of a set of elastic rods with different length. Based on this assumption, a novel numerical model is proposed to simulate the deformation of the catheter. Moreover, based on the characteristics of the contact force, we proposed an approximate method to simulate the virtual contact force. From the experimental studies, the proposed method for simulating catheter interaction is enough to achieve satisfactory outcomes.

Chapter 6

Development of a VR interventional training system

In robot-assisted interventional surgery, surgeon relies on visual and haptic feedback to avoid damaging the blood vessel and guide the catheter to the target area [72]. Therefore, we need to realize two functions for the VR interventional training system: visual feedback and haptic feedback. The haptic feedback is used to provide virtual contact force to the operator during the simulation. This can remind surgeons to avoid damaging blood vessel with excessive force. Visual feedback consists of two parts. One is the simulation of the vasculature, and another is simulation of the behaviors of surgical tools (here mainly refers to the catheter and guidewire). Mesh representation of vasculature and multiple devices interaction are fundamental to interventional simulation.

In order to achieve the above functions, our VR interventional training system includes the master side and VR simulator, as shown in Figure 6-1.

The developed master side is illustrated in Chapter 2 and 3. The master side has realized two functions: measuring the motion of operator and providing the haptic force to operator. The developed VR interventional training system is an extension of the endovascular robotic system. Because the developed master side can be used for both the endovascular robotic system and the VR interventional training system, the proposed system improves training and reduces the cost of education.

The VR simulator is used to construct the virtual interventional environment. In the context of computer-based simulation of catheterization procedure, the virtual interventional environment can be established by patient-specific data. This makes the interventional training no longer limited to a few vasculature models, while reducing training costs. In order to realize interventional simulation, the simulator need to contain two functions: reconstructing the vasculature mesh and simulating the behaviors of the surgical tools.

Vascular reconstruction is used to generate the vasculature mesh for the interventional training. The vasculature mesh includes classical vascular model (cardiovascular model, cerebrovascular model, etc.) and patient-specific vascular model. These vasculature models are reconstructed by iso-surfacing its segmented volume data. For vascular reconstruction, our group proposed a hybrid method for 3D vascular reconstruction. This method can reconstruct vascular model based on computed tomography (CT) or magnetic resonance angiography images [73]-[77]. The normal images to remove human bones and other soft tissues, thereby remaining the data of blood vessel, and this method is adaptable to calculate the whole vascular structure.

In Chapter 4, we proposed a centerline extraction method. This method can extract the centerline and vessel radius from vasculature mesh. This method is applied in our VR interventional training system to help to realize collision detection. The simulation of the behaviors of the surgical tools is used to simulate the deformation and virtual contact force. This can make the simulation closer to the real surgeries. In Chapter 5, a novel method for simulating catheter interaction has been proposed to solve this problem.

Simulation of the behaviors of surgical tools is a challenging task for virtual interventional radiology. At present, there is still no perfect way to solve this problem. Current research, such as using FEM method or shared centerline method, is complicated, and it need a lot of time to solve the model. Moreover, these methods didn't consider the virtual contact force.

Our method can simulate the catheter shape and provide virtual contact force. However, it still cannot fully reproduce the behavior of the real catheter. One of the problems is that in real-life interventional procedure, the collision point between the catheter and the blood vessel wall is not constant. Since blood vessels are smooth and dynamic, the collision point is not fixed at a certain point. The movement of the collision point will change the shape of the catheter. Moreover, we use a rigid vessel model to establish the VR vessel model, not human vasculature. The human vascular system is a dynamic system with a beating heart. The future work will establish dynamic human vascular system, including heartbeat simulation, hemodynamics-based blood simulation, and add these to our VR interventional system. In the future, we will improve our method to solve this problem.

In this chapter, a novel VR interventional training system was developed to improve surgeon's surgical skills. We design two experiments to evaluate the performance of the system. First experiment is used to verify the master side in endovascular robotic system. The *in vitro* result shows that the haptic force feedback was a benefit for providing natural haptic sensation and reducing the human cognitive workload as well as maintaining the safety of surgery. The proposed master side has potential to be used in robot-assisted interventional surgery. Second experiment is used to verify the performance of the VR interventional training system. From the experimental studies, the proposed method for simulating catheter interaction is enough to achieve satisfactory outcomes. The average running time for solving the deformation between two collision points is 12.27 msec, which satisfies the requirement of interventional simulation. These two experiments shows that the haptic force interface can be used for both endovascular robotic systems and VR interventional training systems. The VR simulator can simulate the catheter shape and provide virtual force feedback.

Chapter 7

Conclusions and future work

7.1 Contributions

In this thesis, a novel virtual reality interventional training system has been proposed for robot-assisted interventional training. Our system includes two parts: the master side and the VR simulator. This system is an extension of the endovascular robotic system. Because the master side of this system can also be used in the endovascular robotic system, the proposed system improves training and reduces the cost of education.

For the master side, since the closed loop system in the presented haptic force interface is based on force signals, the accuracy of provided haptic force feedback is confirmed. The haptic force is generated by the spring-based force generator. Due to the elasticity of the blood vessel, the spring is more suitable to simulate the contact force between the surgical tools and blood vessel wall. A rigid metal rod is used to control the system. As an alternative to a catheter, it can keep the natural manipulation skill of surgeon and transmit the haptic force to the operator effectively. Moreover, a collision protection function was developed to assist surgeon to avoid catheter-tissue collision. If the algorithm detects a collision, the haptic force interface will provide a warning force to notify the operator, and the operator will change operation (retraction or rotation) to reduce damage to the vessel. From the experimental studies, the haptic force interface can provide precise force to the operator, and the motion accuracy is enough for the robot-assisted interventional surgery. The proposed collision detection algorithm can detect the collision in different surgical stages. Since no additional sensors or special environment are needed, the proposed collision detection algorithm can be easily applied to other endovascular robotic systems without significant modification. The *in vitro* result shows that the haptic force feedback was a benefit for providing natural haptic sensation and reducing the human cognitive workload as well as maintaining the safety of surgery. The proposed haptic robot-assisted catheter operating system with collision protection function has potential to be used in robot-assisted interventional training.

For the VR simulator, a novel method is proposed to simulate the behaviors of surgical tools, including the deformation and virtual contact force. Our method discretizes the catheter by the collision points. For each part between two adjacent collision points, the catheter is treated as a thin torsion-free elastic rod. Therefore, the catheter model is as a structure composed of a set of elastic rods with different length. Based on this assumption, a novel numerical model is proposed to simulate the deformation of the catheter. Moreover, based on the characteristics of the contact force, we proposed an approximate method to simulate the virtual contact force. From the experimental studies, the proposed method for simulating catheter interaction is enough to achieve satisfactory outcomes. The average running time for solving the deformation between two collision points is 12.27 msec, which satisfies the requirement of interventional simulation. In the future, we will improve the performance of the catheter interaction simulation and apply the system in interventional training.

The contributions of the research in this thesis consist in the following aspects:

1) A novel haptic force interface with collision protection function was presented to provide high accuracy haptic force feedback and improve surgical safety for robot-assisted interventional surgeries. Since the closed loop system in the presented haptic force interface is based on force signals, the accuracy of provided haptic force feedback is confirmed. Moreover, a collision protection function with a proximal-force-based collision detection algorithm was proposed to improve surgical safety. The results demonstrated the usability of the developed haptic robot-assisted catheter operating system with collision protection function.

2) A novel method to solve catheterization modeling during interventional surgery simulation was presented. This method discretizes the continuous catheter by the collision points. The catheter between two adjacent collision points is treated as thin

torsion-free elastic rods. The physical behavior of the rod is predominately governed by applying force at collision points. Moreover, a centerline extraction method was proposed to obtain vasculature centerline. The centerline is used to detect the contact and encourage operators to move the catheter/guidewire along the centerline to reduce collision. The performance of our method is experimentally validated.

3) A novel VR interventional training system was developed to improve surgeon's surgical skills. The proposed training system includes a novel haptic force interface and VR simulator. The haptic force interface can be used in endovascular robotic systems and VR interventional training systems simultaneously. The VR simulator can simulate the catheter shape and provide virtual force feedback. The results show that the proposed VR interventional training system has potential to be used in robot-assisted interventional surgical training.

7.2 Future works

In the future, we will improve the performance of the system and validate the system in in real in vivo experiments on animals. Moreover, we will improve the performance of the catheter interaction simulation and apply the system in interventional training.

Publication List

International Journal papers:

1. **<u>Peng Shi</u>**, Shuxiang Guo, Linshuai Zhang, Xiaoliang Jin, Hideyuki Hirata, Takashi Tamiya, Masahiko Kawanishi, "Design and Evaluation of a Haptic Robot-assisted Catheter Operating System with Collision Protection Function," IEEE Sensors Journal, vol. 21, no. 18, pp. 20807-20816, 15 Sept.15, 2021, doi: 10.1109/JSEN.2021.3095187.
2. **<u>Peng Shi</u>**, Shuxiang Guo, Xiaoliang Jin, "Centerline Extraction of Vasculature Mesh for Virtual Reality Interventional Training Systems," International Journal of Mechatronics and Automation, 2021, In press.
3. **<u>Peng Shi</u>**, Shuxiang Guo, Xiaoliang Jin, Hideyuki Hirata, Takashi Tamiya, Masahiko Kawanishi, "A Novel Catheter Interaction Simulating Method for Virtual Reality Interventional Training Systems," IEEE Sensors Journal, Under review.
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5. 10. Xiaoliang Jin, Shuxiang Guo, Jian Guo, **Peng Shi**, and Xinming Li, "Preliminary Method for Reducing Contact Force between Catheter Tip and Vessel Wall in Endovascular Surgery," in Proceedings of 2021 IEEE International Conference on Mechatronics and Automation, pp.1055-1059, 2021.
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7. Xiaoliang Jin, Shuxiang Guo, Jian Guo, Linshuai Zhang, **Peng Shi**, Dapeng Song, Weihao Wang, "Development of a Grasper for Vascular Interventional Surgery Robotic System," in Proceedings of 2019 IEEE International Conference on Mechatronics and Automation, pp.2262-2266, 2019.
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Biographic Sketch

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