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論文内容の要旨

1.Background

Minimally invasive surgeries (MIS) have become the most common surgical techniques of treating cardiovascular diseases such as the atherosclerosis, thrombus, and aneurisms. However, prolonged exposure to X-ray radiation during surgery impacts on the interventionalists' health. Endovascular robotic systems have been developed to release surgeon from the risks of radiation and heavy radiation-shielded garments. However, current robotic systems use manipulator, joystick, mouse and touch screen to control robot. This operation is different from classical surgeries. Surgeons need practice to be proficient in using endovascular robotic systems. Traditional interventional 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 simulators for endovascular robotic systems were developed as a means of improving training and reducing the costs of education.

2.Challenges

1)Most of existing VR interventional training systems is used for traditional interventional training, which are not suitable for robot-assisted interventional surgery.

2)A satisfactory artificial haptic force interface that can provide high-precision force feedback has not yet been realized.

3)VR interventional training systems lack intuitive human-computer interaction, which can reproduce the dynamical behavior of catheter and guidewire.

3.Research purposes and approaches

In order to provide interventional training which is suitable for robot-assisted intervention surgery, a novel virtual reality interventional training system has been proposed.

To achieve the mentioned research purpose above, the research approaches are described as follows:

1)Design a novel haptic force interface, which can be applied to endovascular robotic system and VR interventional training system simultaneously.

2)Propose a novel catheter interaction simulation method which can simulate catheter's shape and provide virtual force feedback.

3)Develop a virtual reality interventional training system that allow surgeons to do VR interventional training tasks.

4.Research topics

I.Design and evaluation of a novel haptic force interface with collision protection function.

II.Catheter interaction simulation in virtual reality interventional training systems.

III.Development of a virtual reality interventional training system for robot-assisted interventional surgery.

5.Conclusions and future work

In this research, a novel virtual reality interventional training system has been proposed for robot-assisted interventional training.

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.

We will focus on the performance evaluation of the proposed virtual reality interventional training system in the future.

審査結果の要旨

The defense committee examined the PhD thesis entitled "Study on a Novel Virtual Reality Interventional Training System for Robot-assisted Interventional Surgery", submitted by the above applicant for a doctoral degree. The aim of this study is to develop a novel virtual reality interventional training system to realize high accuracy force feedback, the simulation of the dynamical behavior of catheter and guidewire and the intuitive human-computer interaction interface for virtual reality interventional training.

The dissertation consists of 7 chapters as follows.

Chapter 1: Introduction

Endovascular robotic systems have been applied in robot-assisted interventional surgery to improve surgical safety and reduce radiation to surgeons. This surgery requires surgeons to be highly skilled at operating vascular interventional surgical robot. Virtual reality (VR) interventional training systems for robot-assisted interventional surgical training have many advantages over traditional training methods. 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.

Chapter 2: Design of the master side

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.

Chapter 3: Z-score based collision protection function

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.

Chapter 4: Centerline extraction method

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.

Chapter 5: Catheter interaction simulation

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.

Chapter 6: Development of a VR interventional training system

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. Second experiment is used to verify the performance of the VR interventional training system.

Chapter 7: Conclusions and future work

The conclusions of this thesis are as follows:

1.The mean error of the haptic force interface is 0.027 N. The perceptual resolution in force discrimination, as measured by the just noticeable difference (JND), is 7-10% over a range of 0.5-200N. Thus, the proposed spring-based haptic force interface can accurately provide the haptic force.

2.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.

3.The improved centerline extraction method is sufficient to extract a complete centerline, and the pre-processing can effectively reduce the number of vertices.

4.During the simulation, the average running time for solving the deformation between two collision points is 12.27 msec. This satisfies the requirement of interventional simulation.

5.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.

6.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.

The achievements presented in the PhD thesis were published in the following two journal papers and one conference paper as the first author. All the publications were made during his doctoral period.

1.Peng Shi, 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, 2021. (IF: 3.301)

2.Peng Shi, Shuxiang Guo, Xiaoliang Jin, "Centerline Extraction of Vasculature Mesh for Virtual Reality Interventional Training Systems," International Journal of Mechatronics and Automation, 2021, In press. (EI)

3.Peng Shi, Shuxiang Guo, Xiaoliang Jin and Dapeng Song, "A Two-channel Haptic Force Interface for Endovascular Robotic Systems," in Proceedings of 2020 IEEE International Conference on Mechatronics and Automation, pp.1602-1606, 2020. (EI)

最終試験結果の要旨

令和 4 年 2 月 3 日に公聴会ならびに最終試験を実施した。公聴会では、申請者が学位論文の内容に関する発表を行った（約 50 分間）。その後、口述試験として学位論文の内容にかかわる審査委員の質疑に的確に答えることを求め、更に学位論文に関連した分野の専門知識を確認することで最終試験とした（約 40 分間）。

最終試験における学位論文に対する質疑応答の概要は以下のとおりであり、審査申請者はすべて的確に回答した。

●開発した血管モデルについて、物理特性をどのように表現するか。

（回答）開発した血管モデルは幾何情報だけではなく、弾性と粘性の物理特性を血管モデルに含まれている。実際の生体血管に同じな物理特性をもっている。

●カテーテル操作支援システムを開発する目的は何か。

（回答）現段階では、医学部の４年生－５年生の脳神経外科におけるカテーテル実習のた

めに、カテーテル操作支援システムを開発した。熟練医者の操作スキルを抽出し、モデル化、訓練することにより、高度専門医の育成、および臨床応用を目指す。
●提案したロボティックカテーテル操作システムの新規性は何か。
（回答）従来のマスターシステムでは、ハンドルやジョイスティックを用いていたが、提案した新しい方法は、実際の手術用カテーテルを用いて測定するため、機械に慣れてない医師でもすぐに扱うことができる新規性がある。新型触覚特性を持つマスターオペレーティング·システムを開発、先端とサイドの両方の力情報をモニターリング可能にした。カテーテルインターベンション力モデルを作成、触覚フィードバックと視覚的な情報フィードバックの効果を検証、開発されたシステムが操作性と安全性を高めることを実証した。
●開発したカテーテル操作支援システムを利用してどのように初心者を訓練するか。
（回答）熟練医者の操作スキルを抽出して、データベースを構築し、熟練医者の操作スキルを含めたデータベースに基づいて初心者を訓練する。さらに、患者の血管 CT と MRI データを開発した VR システムに導入して、患者の血管モデルを再構築する。実際の手術をする前に医者が訓練できるため、手術の安全性を高めて医療事故を減少できる。
本審査委員会における審査は、学位論文の内容、研究方法論を確認しようとするものである。
　本審査委員会は、提出された博士学位請求論文が博士（工学）の学位に値するものであり、かつ審査申請者は専門領域に関する十分な学識と研究能力を有するものと判断した。以上より、本最終試験の評価を合格とする。