博士論文（要約）

Virtual Reality Simulation in Robotic Surgery

（ロボット手術におけるバーチャルリアリティシミュレーションに関する研究）

エレディア　ペレス　　サウル　アレクシス

Minimally Invasive Surgery (MIS) is a surgical technique based on the access to inner cavities via multiple small incisions in the patient's body, less invasive than its open surgery counterpart. The advantages of MIS are less pain, smaller scars, and faster recovery time. However, higher level of surgical skills is required, the learning curve is steeper, and the required procedure time is longer. In the first type of MIS, called Endoscopic Surgery, tiny cameras and surgical instruments are inserted through the patient's mouth, nostril, or small incisions, to operate and view inside of the patient's body. In the second type of MIS, Robotic Assisted Surgery, the insertion and manipulation of the surgical tools and endoscope are assisted by robots.

Robotic surgery is characterized by the following advantages: It is possible to see diseased regions that normally are obscured by internal organs or bones; it makes it possible to conduct surgical operations in narrow spaces and behind organs with precision and high accuracy, which is difficult using conventional surgical techniques; and it enables the performance of telediagnosis and telesurgery. With the advancement of technology in the medical field, more complex types of surgery procedures have been devised to better rehabilitate patients or to help handle patients with more complicated situations.

The da Vinci surgical system (Intuitive Surgical, USA) is the most widespread medical robotic platform in use across the world for a wide variety of laparoscopic procedures. This master–slave robotic system provides the surgeon with an immersive operating environment with high-quality stereo visualization and a man–machine interface that directly connects the movement of the hand of the surgeon to instrument tip movement inside the patient. However, some surgical procedures, especially in the field of microsurgery, such as neurosurgery and pediatric neonatal surgery, are technically difficult to be implemented using the da Vinci robotic system because of the size of the surgical instruments. High-precision robotic manipulators equipped with finer robotic surgical instruments to target smaller workspaces becomes a necessary technology.

To overcome this limitation of the existing robotic surgical systems, the Mitsuishi Harada Laboratory at The University of Tokyo has been conducting research on robotic systems and developing surgical robots targeting MIS and microsurgery. Within this research line, a versatile robotic system for narrow workspaces called SmartArm was developed in conjunction with partner universities and companies. The SmartArm robotic system has two industrial-type robotic arms and four degrees-of-freedom (DoF) dexterous tools, with a total of 9 DoF for each arm plus a gripping DoF. The SmartArm includes customizable virtual fixture based on geometrical primitives targeting different surgical procedures that are impossible for the da Vinci system. The operability of the SmartArm in neurosurgery and pediatric surgery scenarios have been validated through experiments using anatomically accurate phantom models.

Despite the benefits of robotic assisted surgery compared to manual open surgery, the surgeons still need to train to adapt themselves to the newer surgical systems technologies. Virtual Reality (VR) simulators provide a computer-generated realistic environment where surgeons can be trained with no risk to patients. The repeatability and reusability offered by VR-based simulators can improve surgical skills by allowing repetitive practice on different scenarios. In addition, these simulators can also provide objective evaluation of task performance and assessment of competency, and those may be unmeasurable via traditional means.

The existing VR robotic surgery simulators exclusively focus on the training of surgical procedures on the da Vinci Surgical System. These systems are commercialized at high cost as closed code software, therefore cannot be modified to simulate other type of robot or surgery, as it would be desired to address microsurgery using the SmartArm robotic system. Moreover, these systems include interactive task for learning and training, but not intended for research in robotic microsurgery.

A VR simulator targeting microsurgery using the SmartArt system might support the research and development of such robotic system towards its future insertion in the operating room. Particularly, to address the following issues: (1) Deep learning-based segmentation of robotic surgical instruments requires manual annotated training datasets, which is a time-consuming task. A photorealistic VR simulation might have the potential to generate synthetic training datasets to train deep learning models that can be applied on real data. (2) Hands-on training using the physical robot on phantoms is impractical due to the high cost and risk of damage of the prototype. A physically plausible VR simulation for robotic surgery training might short the learning curve of the SmartArm robotic system in the realization of suturing tasks.

With those ideas in mind, the main objective of the proposed research is to develop virtual reality simulators for minimally invasive surgery to contribute to the development and research in the field of medical robotics. This dissertation contributes to the virtual reality simulation of robotic surgery by presenting a methodology for plausible simulation of soft body dynamics, applied to the real-time simulation of soft tissues, surgical suture, and flexible robotic instruments.

This thesis is divided into the following three parts:

The first part encompasses the development of the VR simulation system. For real-time physics-based surgical simulation the NVIDIA PhysX engine was utilized to speed up the development process. Using a rigid body dynamics approach, the surgical suture was simulated as a serial chain of capsule-shaped rigid bodies connected by spherical joints. The needle was simplified as a rigid body connected to an ending of the tread by a fixed joint. To simulate the deformable bodies such as vessels or membranes, a network of interconnected rigid bodies was utilized to model the viscoelastic behavior similarly to mass-spring models. To animate the high-resolution visual models, an animation technique known as skeletal animation was employed. The same approach was applied to simulate the flexible robotic instruments. It was achieved real time plausible simulation of robot-assisted suturing task. The interactive simulation system uses the same master interface as the physical robot, composed by a pair of commercial haptic devices. The developed VR simulation system is capable of haptic feedback, and implements photorealistic 3D rendering.

The second part covers the topic of advanced control of the surgical robot using VR simulation, subdivided into two main stages. Firstly, using VR simulation of a hypothetical scenario of transsphenoidal neurosurgery using a prototype of a 7 DoF surgical robot, a novel dynamic motion scaling (DMS) approach was evaluated. After the execution of validation experiments with naïve and expert surgeons, it was concluded that DMS has the potential to enhance the accuracy and safety of the robot manipulation during the realization of complex tasks. However, migrating such feature from VR simulation to the physical robot requires accurate calibration of the position and orientation of the robotic instruments. In this direction, the next stage studies the application of physically based VR simulation with photorealistic rendering in the generation of synthetic datasets for the training of deep learning models for the semantic segmentation of robotic surgical instruments on real images. After executing validation experiments, it was concluded that deep learning models training with photorealistic VR-generated data performed well on real data during the segmentation task of the robotic surgical instruments.

The third part of this work covers the application of VR simulation for the advanced surgical training of robotic pediatric surgery. Pediatric robotic surgery is a difficult task because of the delicacy of tissues and small workspace. Before using the SmartArm robotic system, the surgeons need to train. Although child-sized physical models of the chest have been developed for surgical training and surgical skills assessment, training on the physical robot is impractical because of the high operative cost and the risk of damage of the prototype. To support the training of the SmartArm robotic system, it was developed a VR simulator for training of pediatric surgery, focusing in the interactive suturing task. To validate the proposed VR simulator experiments with apprentices and expert surgeons will be conducted.

In sum, the VR simulation systems developed in this work may contribute to the field of medical robotics. In this study VR simulation was utilized to generate synthetic training datasets for deep learning models for the semantic segmentation of robotic surgical instruments. The proposed methodology alleviates the labor of manual annotation of the training datasets. The next steps in this direction will be the pose estimation of the robotic surgical instruments to achieve accurate calibration of the robot. In addition, the presented work might be useful for surgical training as the SmartArm robotic system matures towards their commercialization and use at medical institutions all around the world.