早稲田大学大学院 先進理工学研究科

博 士 論 文 概 要

論 文 題 目

Study on Trajectory Planning of Surgical Manipulator Considering Visualization and Operability in Narrow Workspace for Pediatric Surgery

小児外科における狭い空間での視野確保と操作性を考慮したマニピュレータの動作計画に関する研究

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Minimally invasive surgery (MIS) is a particular way of performing surgery by using smaller instruments and smaller incisions than traditional surgical methods. The goal of the MIS is to perform operations through very small incisions, a relatively smaller size of the incisions than that used in traditional surgery with equal or superior clinical outcomes and less impact on a patient's body and organs. Generally, surgical instruments and endoscope approach the surgical site through small incisions in the MIS process. In order to arrange the instruments and endoscope at the surgical site, an inflated cavity is usually created via an artificial pneumoperitoneum at the beginning of the MIS. This method takes advantages of using the elastic sealed cavity of human body, such as the abdomen, to build the pneumoperitoneum. Generally, a 40~50 mm incision is created for adult esophageal atresia repair surgery. However, to pediatric patient, such as the congenital esophageal atresia surgery, the workspace is about 30x30x30 mm near the fourth intercostal of the right side of chest, which is very tight to place two or three manipulator and an endoscope simultaneously. Furthermore, the surgical manipulator can easily to block endoscopic view during performing surgical procedures in the narrow space.

The robotic assistance technologies extended the capabilities of surgeons by progress of computer-aided technology and dexterous manipulator. Compared with the traditional MIS, utility of robotic assistance surgical system breaks the law that surgeon must perform operation besides operating table. In order to smoothly operate in narrow workspace, forceps manipulator should be designed with small size and high rigidity. Compact surgical manipulator with multiple Degree of Freedoms (DoFs) is becoming hot issue used for tissue intervention. In the robotic assisted system, remote control is commonly employed to map the movement of a user input to the surgical manipulator. Remote control, also known as master-slave control, is widely used in robotic surgical systems. It provides beneficial results via taking advantages of less restriction by space in operation room (OR), reduced fatigue to operators because of ergonomic input devices, reduced surgical trauma to patients with dexterous instruments. Based on the configuration of manipulators, mapping relation between master input device and slave actuator would be mathematical computed. Surgeon steer two user inputs to control the slave manipulators through master-slave control architecture during operation, while guided by visual feedback from a visual module. However, although the multi-DoF surgical manipulator improves the dexterity on operation, it poses new challenges on the robotic control. Generally, with the consideration of ergonomics, the master input and the slave manipulator are isomeric, therefore, the surgical manipulator in the slave side cannot complete map the posture of the overall master mechanism. The user of the robotic system mainly pays attention to the position and posture of the forceps of the surgical manipulator during operation. In order to obtain good eye-hand coordination, the posture of master handle in surgeon's vision and that of the surgical manipulator tip in the endoscopic view should be identical. To the redundant serial manipulator, there are many solutions for the redundant joints in the inverse kinematics computation, even though the position and posture of the forceps of the manipulator is unique. In order to select out the optimal solution, the constraints of surgery will be considered. In the pediatric surgery, the MIS can reduce the geometric cut size on the body surface, but increase the risk of hurting pediatric organ by pneumoperitoneum.

In this study, we aim to design a robotic system to assist pediatric Congenital Esophageal Atresia （CEA） surgery. Pediatric CEA is a birth defect that affects the alimentary tract, occurs in approximately 1 in 4400 live births. Pediatric CEA takes several different forms often involving one or more fistulas connecting the trachea to the esophagus. In approximately 85% of cases, the esophagus ends in a blind-ended pouch, rather than connecting normally to the stomach. Without treatment, the infant will soon die due to malnutrition. Currently, the most immediate and effective treatment in the majority of pediatric CEA is a surgical repair to close the fistulas and reconnect the two ends of the esophagus to each other in a 30x30x30 mm workspace. However, current robotic system exposed obvious drawbacks: manipulator with small geometric dimension (diameter <= 5mm) is danger due to high risk of damaging pediatric tender organ; manipulator with large geometric dimension (diameter >= 10 mm) is difficult to operate in narrow space due to the vision shielded by manipulator in endoscopic surgery. In this thesis, the author indicates a compact surgical robot for pediatric surgery. It can realize dexterous operation by two slave manipulators, each with an external diameter of 8 mm at the forceps. In order to reduce the shelter of vision caused by manipulator during operation, an algorithm to control redundant manipulator is developed to map the trajectory while the forceps of manipulator tracking the position and posture of the user input, maintaining triangle formation between slave manipulators and endoscope.

This thesis consists of 6 chapters.

In chapter 1, the author introduces the state of the art of minimally invasive surgery (MIS) as well as the utility of surgical robot, especially in pediatric surgery. The author also presents the remaining problem and technique issue of current robotic system, and states the purpose of this research and the research flow.

In chapter 2, the author describes the typical control method of computer-aided robotic system, and states the control strategy of remote-control robot system. Since this research needs to map the trajectory relation between user input and slave manipulator, the author considers the influence of the mechanism configuration of surgical robot in the control strategy for performing intervention in narrow workspace on surgery.

In chapter 3, the author presents the mechatronics design of pediatric surgical robot. The surgical robot consists of a master console and slave manipulators. The master console is composed of Phantom Omni and foot pedals to generate input signals. In the slave side of surgical robot, it consists of two isomorphic slave manipulators, with total 18 DoFs. Each slave manipulator is composed of a positioning manipulator and a surgical tool manipulator. The positioning manipulator has 4 DoFs, which can achieve translational movements in spatial movement. The surgical tool manipulator employs double screw drive (DSD) mechanism to achieve bendable movements. A single surgical tool manipulator with 5 DoFs and an external diameter of 8 mm consists of two bendable joints and a rotatable forceps. Each bendable joint can realize two bending movements in two orthogonal planes. The rotatable forceps is composed of a rotatable joint and a clipper with opening and closing movement. In this chapter, the kinematics of the slave manipulator is calculated. The simulation results show the overlapped area of two positioning manipulator covers a 30x30 mm zone; and the distal of the surgical tool manipulator can achieve an arbitrary bending movement in 40x40x13 mm workspace by two bendable joints. By integrating tool manipulator with positioning manipulator, the robot system can perform surgical intervention in a 30x30x30 mm workspace in pediatric surgery. The inverse kinematics for calculating active rod's length illustrated that the rod's deviation of bending linkage is less than 3 mm. The experiment to measure the flexible shaft's rigidity show the flexible shaft could keep high rigidity when loaded within 200 g.

In chapter 4, the author proposes a shape optimal algorithm to map the relation between master input and the slave manipulator. The purpose of this algorithm aims to construct a triangle formation between endoscope and the slave manipulators to provide good operability and visualization for robot user. Due to the heterogeneous configuration between the master input and the slave manipulator, the posture of each joint in the master input cannot complete match with the slave mechanism chain. Therefore, the master input just directly control the position and posture of the distal of the manipulator, the redundant joints of manipulator will be controlled by the proposed algorithm. In the first step, the relation between the robot joint's inverse kinematics solution and the disturbance at redundant joint is established. The verification simulation shows that the robotic arm with the inverse kinematic algorithm can accurately track the input ($\Delta_{simulator} < 0.5mm$). Subsequently, a shape optimal algorithm considering the visualization and operability is developed to construct a triangle formation between slave manipulators and endoscope in workspace. Given a tolerable error ($\varepsilon = 0.001$), the adjacent angle deviation between two bendable joints among the 4 quadrants satisfy that $\Delta_{angle\_deviation} < 0.5^{\circ}$. The experimental result of position tracking with the shape optimal algorithm demonstrated that the distal of the manipulator could achieve position error $\Delta_{position\_error} < 1mm$ when loaded within 50 g in two-dimensional plane or loaded within 20 g in three-dimensional space. Therefore, the pediatric surgical robot satisfies the precision requirement of tissue intervention in pediatric CEA surgery.

In chapter 5, the author presents a novel application for reducing operating difficulty to the master-slave robot user. Generally, human being have dexterous hand than the other, therefore, they are willing to use their dexterous hand for important manipulation, even though their both hands are needed in normal operation. The author extends the algorithm referred in chapter 4 by using two endoscopes in the pediatric surgical robot. The two endoscopes located at both sides with respect to the plane, where the both slave manipulators located. Therefore, there are two solutions by combining a single endoscope and two slave manipulators. In addition, the correspondence between the master input and the slave manipulator can be exchanged based on the selection of combination between the endoscope and the slave manipulator. The algorithm guarantees surgical robot user to use their dexterous hands for important operation even performing suture task on both sides of a cut. The experimental results show that the time taken for the same task with the handedness control obviously improves user's performance and the feasibility of suture on an esophagus model by using the developed algorithm.

In chapter 6, the author concludes this research and discusses future work, such as the evaluation of pediatric surgical robot through *in vivo* experiments, and the clinical applications of using pediatric surgical robot as well as the control algorithm in serial robotic manipulator.

In this overall research, the author establishes a compact robot system for pediatric surgery. Considering the narrow space of pediatric surgery, the author proposes an algorithm to control the trajectory of redundant manipulator. From this research, the author establishes a way to perform tissue intervention with surgical robot in narrow workspace for pediatric surgery.

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