早稲田大学大学院 先進理工学研究科

博士論文審査報告書

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 with equal or superior clinical outcomes and less impact on a patient's body than traditional surgical methods. The robotic assistance technologies extended the capabilities of surgeons by progress of computer-aided technology and dexterous manipulator. In master-slave robot system, surgeon steer two user inputs to control the corresponding slave manipulators, while guided by visual feedback from a visual module. Although the multiple Degree of Freedoms (DoF) manipulator improves the dexterity on operation, it poses new challenges on the robotic control. To a redundant serial manipulator, there are many solutions for the redundant joints in the inverse computation, even though the position and posture of the forceps of the distal is unique.

In this study, the author aim to develop a robotic system to assist pediatric Congenital Esophageal Atresia (CEA) surgery. Pediatric CEA is a birth defect that blocks esophagus into two separated segments, occurs in approximately 1 in 4400 live births. Currently, the most immediate and effective treatment is a surgical repair to close the fistulas and reconnect the two ends of the esophagus to each other. Generally, a 40~50 mm incision is created for adult esophageal atresia repair surgery. However, to pediatric patient, 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 manipulators and an endoscope simultaneously. Current robotic system exposed obvious drawbacks: manipulator with small geometric dimension (diameter <= 5 mm) 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 proposes a compact surgical robot for pediatric surgery, which can realize dexterous operation by two slave surgical manipulators, each with an external diameter of 8 mm. By integrating visualization and operability, an algorithm is proposed to control redundant manipulator for performing tissue intervention in narrow workspace.

The thesis consists of six chapters, organized as the followings.

In chapter one, the author introduces the state of the art of MIS as well as the utility of surgical robot, especially for pediatric surgery. The author presents the remaining problem and technique issue of current robotic systems, and states the purpose of this research and the research flow.

In chapter two, the author states the typical control method of robotic manipulator. Since this research needs to map the trajectory relation between user input and slave manipulator, the author proposes a methodology by integrating the influence of the mechanism configuration of surgical robot in the control strategy.

In chapter three, the author presents the mechatronics design of the surgical robot system. It consists of two isomorphic slave manipulators and two visual modules. Each slave manipulator having 9 DoFs in total is composed of a positioning manipulator and a surgical tool manipulator. The positioning manipulator has 4 DoFs, can arrange translational movements in 3D space. 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 for arbitrary bending movement by using double screw drive (DSD) mechanism. The rotatable forceps is composed of a rotatable joint and a clipper with opening and closing movement. The kinematical simulation results show that the robot can perform surgical intervention in a 30x30x30 mm workspace in pediatric surgery, while the active rod's deviation of each 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 four, 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 operability and visualization for robot user. 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 ($\Delta_{simlator} < 0.5mm$). 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 satisfy $\Delta_{angle\_deviation} < 0.5^{\circ}$. The experiment result of position tracking with the shape optimal algorithm demonstrated that the distal of the manipulator can achieve position error < 1mm during trajectory planning when loaded within 50 g in two-dimensional plane or loaded within 20 g in three-dimensional space.

In chapter five, the author presents a novel application for reducing operating difficulty to the master-slave robot user. Generally, human being have one dexterous hand than the other, therefore, they are willing to use their dexterous hand for important manipulation, even though both hands are needed in normal operation. The author extends the algorithm referred in chapter four by using two endoscopes in the pediatric robot system. 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. The handedness control algorithm guarantees the robot operator 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 six, the author concludes this research and discusses future work, such as the evaluation of this robot through *in vivo* experiments, and the clinical applications of using the pediatric robot as well as the control algorithm in other robotic manipulator.

In summary, this thesis suggests a compact surgical robot to assist surgeon for performing tissue intervention in narrow workspace for pediatric surgery. The contribution of this thesis is to develop a pediatric surgical assist robot, and develop a control strategy to provide good visualization and operability for robot user by controlling the redundant manipulator in tight workspace. As mentioned, this thesis contributes to the advancement of robotic technology and pediatric surgical assist technology, and is worth to be awarded the Doctor of Engineering.

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