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主　論　文　の　要　旨

論文題目　**Developing a cooperative robotic-assisted surgical system for endoscopic endonasal surgery**
(経鼻内視鏡手術のための協調ロボットによる手術支援システムの開発)

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論　文　内　容　の　要　旨

Endoscopic endonasal surgery (EES) is a minimally invasive technique for the removal of pituitary adenomas or cysts at the skull base. This approach can reduce invasiveness and recovery time compared to traditional open surgery techniques. However, it represents challenges to surgeons because of the constrained workspace imposed by the nasal cavity and the lack of dexterity with conventional surgical instruments. Robotic systems for minimally invasive surgery have been developed to address manipulation and visualization limitations, but many challenges remain for EES. Previous studies focused on enhancing the surgeon's capabilities during the execution of certain surgical tasks but hindering the execution of other activities. Teleoperation systems, for example, can provide high dexterity surgical manipulation, but require a large, time-consuming setup and the help of assistance staff for tool exchange. They also result in high-cost, bulky solutions that are not suitable for highly constrained procedures such as the case of EES. The interactions between the surgeon and the robot also represent a significant issue as they occur in a dynamic and highly constrained environment, and the robotic system should be able to perceive the environment and the human intention and then adapt to both appropriately and intuitively. Thus, there is a need for surgical systems that can cover the entire EES cycle but maintaining a dexterous, intuitive, and safe operation of the robotic system.

This thesis aims to fill this gap by presenting a cooperative framework for a robotic-assisted surgical system targeting EES applications.

The first contribution of this thesis is to introduce a cooperative human-robot interface for robot-assisted endoscopic endonasal surgery. We evaluated several design concepts to enhance intuitiveness and safety during highly dexterous anatomically constrained surgical tasks in EES. We finally selected a hybrid interface composed of a force-based and a serial-link interface. The surgical task was divided into stages, each of which was concerned with specific challenges and constraints. The force-based interface was chosen for positioning, insertion, and extraction of the articulated forceps because of the simplicity and natural control arising from human-robot physical interaction. During the positioning stage, the robot works in gravity compensation mode and follows the force applied by the surgeon over the interface. Then, the robot constrains the forceps motion along a virtual remote-center-of-motion (RCM) fixed in the nostril during the insertion and extraction states. Once the tool is placed at the target workspace, we use the serial-link interface for precise control of the articulated forceps while keeping a virtual remote-center-of-motion at the nostril. Workspace constraints were implemented based on virtual fixtures to limit the tool workspace and ensure safe motion inside the patient. We defined the constraints from a phantom head to determine the sinus cavity and the dura workspace. We proposed a state-based real-time controller that combined an admittance controller for positioning and insertion/extraction with a position tracker to control the forceps tip during the surgical task, ensuring a smooth transition between these stages. Finally, we compared the performance of our proposed system with the use of conventional surgical instruments in common surgical tasks. A reachability experiment in a phantom head showed the capability of reaching the areas of interest such as the pituitary area in a smooth and precise way compared with the use of conventional instruments. Pick-and-place and block-in-hole experiments were performed to evaluate the manipulation of objects inside the nasal cavity under the anatomic constraints imposed by the nostril. The results showed a noticeable improvement in the motion smoothness. Besides, a needle stitching task was conducted to test the system in the highly dexterous surgical task. The robotic system showed a similar completion time to the manual operation on each phase, except for the regrasping phase, in which passing the needle was challenging because of the requirement of keeping a proper needle orientation. The same experiment showed a reduction in the force distribution applied over the tissue during the needle insertion/extraction.

The second contribution of this thesis is the development of an optimization-based trajectory generation method for robot-assisted stitching based on sequential convex optimization to find the optimal needle trajectory, and a dual concurrent inverse kinematics (IK) solver to constrain the surgical tool around the nostril. The trajectory generation algorithm was capable of generating an optimal trajectory subject to the suturing requirements. The surgeon can regenerate the trajectory online through the user interface. Integrating two constrained IK methods allowed us to achieve the convergence of the solution and meet time constraints. We compared the performance of our system with a manual stitching operation and an autonomous operation. The results showed a noticeable improvement in the stitching success ratio and reduction of the force interaction with the tissue. Although the task completion time did not significantly improve compared with the manual mode, the reliability of using the robotic system was evident as the standard deviation is greatly reduced compared with the manual operation. The robot task completion time could be reduced by increasing the maximum speed allowed for the needle, but it might increase the probability of failing to penetrate the tissue because of needle-tissue interaction forces arising at the needle tip, which could induce undesired changes in the needle orientation. The robot-assisted mode achieved a stitching success ratio of 65%, much higher than that of the autonomous mode (43%) and the manual operation (25%). Unlike the autonomous mode where the speed is fixed, the robot-assisted mode allows the user to freely control the insertion speed and reduce the effect of such interaction forces. Moreover, in the robot-assisted mode, the user can also retract the needle along the optimal trajectory if proper penetration is not achieved (e.g., because of tissue deformation). The constrained motion planning performance was evaluated by the maximum RCM error defined as the minimum distance between the nostril and the forceps shaft. The RCM constraint implemented for the robotic operation (including robot-assisted and autonomous modes) was able to keep the maximum RCM error below 4.2 mm. Besides, the interaction force distribution showed that the use of the robot reduced about 70% of the forces shown in a manual stitching task. This is important to avoid any potential tissue trauma.

The results showed promising performance in controlling and safely constraining the motion of bimanual robot arms with articulated multi-DOF forceps for endoscopic endonasal surgical tasks. However, additional issues still need to be solved, such as the control and integration of additional surgical tools other than grasping (e.g., cutting, drilling), the addition of haptic feedback to the human-robot interface, additional factors for the task modeling such as light, tool collision, needle deflection, and tissue deformation, and characterization of additional suturing subtasks such as knot tying and needle passing for a full suturing performance. Finally, further experimentation would be required to establish a clear performance evaluation of the proposed system in a realistic scenario including subjects with prior surgical training. Future research direction is dedicated to solving these issues.