論 文 の 内 容 の 要 旨

論文題目　Human-Robot Collaborative Surgical System toward Automated Operations
（手技の自動化に向けた人間・ロボット協調手術システムに関する研究）

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The automation technology is very promising in surgical robotic applications especially for the repeated tasks that need high accuracy because the autonomous robots can perform task with higher precision and speed than human operators. However, there are many disturbance and noise in the information that the robots can use, and this may lead to failures in automation. On the other hand, human operators are good at perceiving unstructured environments and immediately reacting to unexpected events. By combining strengths of autonomous robots and humans operators, this dissertation presents a human-robot collaborative robotic system for automated surgery. In the collaborative system, desired trajectory is abstracted and learned from preoperative demonstrations by surgeons, and the robot executes the learned trajectory autonomously. The planned trajectory is overlaid on the microscopic view, and the operator of the robot can approve or modify the trajectory by applying force to the input device. This collaboration method improves the safety in the surgical automation by fully exploiting the robot’s advantages and surgeons experience.

This kind of human-robot collaborative system requires the system to be integrated with several functional components. Therefore, four research keywords are defined in this work such as perception, manipulation, automation, and intervention. The perception is an issue to estimate the state of the robotic forceps. The manipulation is a positioning function of the robotic forceps based on visual information. The automation is learning and reproduction methods of surgical tasks. Finally, the intervention is an interface between human operators and robotic systems to guide the automated robotic motions by surgeons.

The first research topic is perception problem. The robust forceps tracking method under a microscope is proposed for this issue. Forceps tracking is an indispensable function of high level surgical assistance such as visual servoing and motion analysis. Therefore, a robust and efficient tracking algorithm capable of estimating the forceps tip position in an image space is required. Our approach to cope with this problem is to fuse visual tracking data with kinematic information. In visual tracking, the full state parameters of forceps are estimated using the projective contour models generated from the 3-D CAD model of the forceps. The likelihood of the contour model is measured using the distance transformation to enable fast calculation, and the particle filter estimates the full state of the forceps. For more robust tracking, the visual tracking result is combined with kinematic data that is obtained from forward kinematics and hand-eye transformation. The fusion of visual and kinematic tracking data is performed using an adaptive Kalman filter, and the fused tracking enables the reinitialization of visual tracking parameters when a tracking failure occurs. Experimental results indicate that the proposed method is accurate and robust to image noise, and forceps tracking was successfully carried out even when the forceps was out of view.

For the manipulation issue, autonomous positioning system using visual servoing is proposed. Positioning of surgical robotic forceps based on visual feedback is the first step toward autonomous surgical systems that can make full use of the robotic system. To achieve high positioning accuracy, visual servoing technique is utilized in many applications. However, in visual servoing, we cannot control the trajectory of motion in Cartesian space. Undesired behavior of forceps may make damage to tissue or blood vessels. To cope with the problem, we propose a vision-guided positioning system by separating z-axis motion from x-y plane motion. The interaction matrix is decomposed into positioning (x-y plane) and approaching (z-axis) components. Approaching velocity is computed on the basis of difference of disparity that is a dominant factor for approaching, and then positioning velocity is yielded by reformulated interaction matrix. The experimental results showed that the proposed servoing method can control the trajectory in Cartesian space by adjusting approaching coefficient. Using the proposed method, a simple point-to-point task such as needle gripping is successfully performed.

Thereafter, the third research topic regarding automation is addressed. The automation technique is one of the solutions to improve the precision and speed of a variety of the tasks. Therefore, it is widely used for industrial robots in the past decades, and it can be also used for surgical robots to a certain extent. In surgical automation, two functions should be implemented; learning and reproduction. For learning method, we use Gaussian Mixture Model to learn the necessary trajectory for a certain surgical task. After training the task, Gaussian Regression provides an optimal trajectory from several demonstrations. Once the optimal trajectory obtained, the reproduction is carried out with the forceps tracking and visual tracking by tracing the whole desired trajectory. By integrating the functions of forceps tracking, visual servoing, and task learning, the automated task can be realized with the advantages of the reduced completion time and low motion deviation. However, the constraint for the automation is the structured environment, and it is difficult to apply the full automation to surgical tasks which contains many unpredictable conditions.

The fourth research topic is intervention for human-robot collaborative system. In the collaboration method, a commercial haptic device is utilized. The haptic device has two basic interfaces with the operator; force feedback and force input. In our method, the robot provides the operator with force feedback to indicate the planned motion from demonstrations. The surgeon inputs force to the haptic device so that he/she can supervise the automated robotic motion. The operator can approve, accelerate, modify, and terminate the automated motion by judging the current situation from the microscopic view. The prototype of the human-robot collaborative system was developed, and the feasibility of the developed system was demonstrated using simulated surgical tasks.

By integrating the four research topics aforementioned, I proposed the new concept of human-robot collaboration, and developed a platform of human-robot collaborative surgical system toward automated operations. In the experiments, the several surgical tasks were conducted to validate the feasibility of the proposed system. The experimental results demonstrated that unpredictable and undesirable situations can be dealt by the surgeon’s guidance. The human-robot collaboration can provide a new way toward the clinical use of autonomous manipulation since its safety is ensured by the surgeon while benefiting from precision and speed of autonomous systems.