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Image Processing for Autonomous Positioning of Eye Surgery Robot in Micro-Cannulation

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Abstract

Vitreoretinal surgery tasks are difficult even for expert surgeons. Therefore, an eye-surgery robot has been developed to assist surgeons in performing such difficult tasks accurately and safely. In this paper, the autonomous positioning of a micropipette mounted on an eye-surgery robot is proposed; specifically, the shadow of the micropipette is used for positioning in the depth direction. First, several microscopic images of the micropipette and its shadow are obtained, and the images are manually segmented into three regions, namely, the micropipette, its shadow, and the eye ground regions. Next, each pixel of the segmented regions is labeled, and labeled images are used as ground-truth data. Subsequently, the Gaussian Mixture Model (GMM) is used by the eye surgery robot system to learn the sets of the microscope images and their corresponding ground-truth data using the HSV color information as feature values. The GMM model is then used to estimate the regions of the micropipette and its shadow in a real-time microscope image as well as their tip positions, which are utilized for the autonomous robotic position control. After the planar positioning is performed using the visual servoing method, the micropipette is moved to approach the eye ground until the distance between the tip of the micropipette and its shadow is either equal to or less than a predefined threshold. Thus, the robot could accurately approach the eye ground and safely stop before contact. An autonomous positioning task is performed ten times in a simulated eye-surgery setup, and the robot stops at an average height of 1.37 mm from a predefined target when the threshold is 1.4 mm. Further enhancement in the estimation accuracy in the image processing would improve the positioning accuracy and safety.

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1. Introduction

Extremely delicate tasks such as peeling of the 2.5-µm inner limiting membrane (ILM) and cannulation of retinal blood vessels that are approximately 100 µm in diameter are performed in vitreoretinal surgery. Such tasks are difficult even for expert surgeons. The authors of the present work have been developing a master-slave eye surgery robot to assist surgeons in performing the aforementioned tasks and have successfully demonstrated the high-accuracy positioning of a micropipette mounted on the robot [1]. In the system, the hand motion of the operator measured with a master manipulator was scaled down with a motion-scaling ratio of 1/40 using the master-slave control. However, the accuracy of the tool positioning was subject to the skills of the operator in the master-slave control.

Several groups have studied control automation of surgical robots. The works in [2, 3, 4] are about the automation of surgical robots for general surgery. Sen et al. studied a needle path planning method for autonomous skin-suturing and demonstrated multi-throw skin-suturing using a phantom [2]. They developed a 3D-printed suture-needle angular positioner, which attached to the needle driver of a da Vinci surgical

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system. The angular positioner facilitated the grasping of a curved needle in the desired orientation. The needle grasped by the positioner was placed in a constrained needle path using predefined needle entry and exit points. Murali et al. proposed the automation of simple surgical tasks by using the learning-by-observation method [3]. Their learning-by-observation process is based on the finite state machine. They demonstrated debridement of 3D viscoelastic tissue phantoms as well as pattern cutting of 2D orthotropic tissue phantoms. McKinly et al. developed interchangeable surgical tools, which were attached to the da Vinci needle driver of a da Vinci Research Kit [5]. They demonstrated autonomous tumor resection in a phantom experiment, including the detection of the tumor location, exposing and extracting a simulated tumor, and fluid injection to seal the simulated wound [4].

Regarding vitreoretinal surgery, Becker et al. studied vision-based control of a handheld surgical micromanipulator using virtual fixtures for cannulation of retinal blood vessels as well as ILM peeling [5]. The same research group also studied semi-automated intraocular laser surgery using virtual fixtures for their handheld device [6]. These studies demonstrated autonomous navigation of a handheld instrument, where the position information was calculated using a three-dimensional (3D) reconstruction of stereomicroscope images. However, the surgeon observes the patient’s eye ground through a surgical contact lens placed on the eye, the cornea, and the crystalline lens. A liquid is injected to replace the vitreous body. Thus, accurate stereo calibration is difficult in clinical applications. To this end, we propose the automation of robotic tool positioning that does not require stereo calibration.

Currently, we are working toward the complete automation of a cannulation procedure. In a previous work, we proposed autonomous positioning of our eye-surgery robot and validated its performance in an experiment [8]. Image-based visual servoing was used for planar positioning, and a subtle distortion in the microscopic image by physical contact between the eye ground and a micropipette tip was detected for the positioning in the depth direction. Accurate detection was feasible; however, a safer method was needed to prevent possible damage to the eye ground due to physical contact. In a new scenario in the present study, the eye surgery robot automatically and accurately approaches a predefined target in the eye ground and then stops to be switched to autonomous injection, which is to be developed. This paper describes the autonomous positioning of a micropipette in the depth direction using its shadow. This method can be practical as surgeons use shadows to position instruments in the depth direction in vitreoretinal surgery. The appearance of shadows is not affected by the astigmatism as well.

This paper is structured as follows. Section 2 describes the proposed autonomous control method. Section 3 describes an experiment carried out to evaluate the proposed method. Section 4 discusses the results of the experiment, and the conclusion and future work are discussed in Section 5.

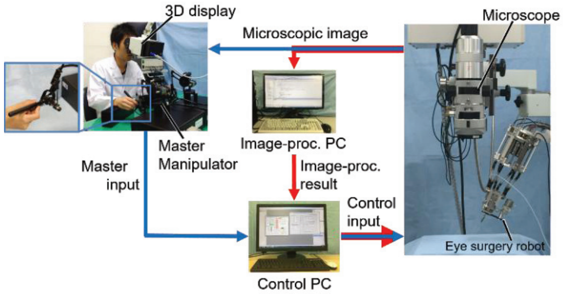

Fig. 1 Eye surgery robot system. Blue arrow: Master-slave mode flow. Red arrow: Autonomous micro cannulation mode flow.

2. Autonomous position method

The eye surgery robot reported in [1] is used for the present study. A green micropipette with a tip diameter of approximately 0.05 mm was mounted on it, and a surgical drape was used to simulate the eye ground. Figure 1 shows the control flows for the master-slave and autonomous position modes (Fig. 1).

In the autonomous positioning mode, several microscopic images were transmitted to the image- processing PC, and the color features of the micropipette, its shadow, and the simulated eye ground were learned in advance. First, the real-time microscopic image was processed, and the tip positions of the micropipette and its shadow were estimated using the learning data. Next, the current tip positions were sent to the control PC. The micropipette was controlled to be placed at a predefined target point in the microscopic view using the visual servoing method. Subsequently, the robot approaches the eye ground until the distance between the estimated tips of the micropipette and its shadow decreases to a predefined threshold. The details of the algorithms are described in the following subsections.

2.1. Estimation of the position of the micropipette tip and its shadow in the microscopic image

Some instrument detection methods were reported in [9, 10, 11], and accurate detections were demonstrated. In our method, a relatively simple method was employed; specifically, the Gaussian Mixture Model (GMM) [12] was used to estimate the shape of the tips of the micropipette and its shadow in the microscopic image. GMM was chosen after a preliminary experiment comparing GMM with the Support Vector Machine (SVM), and GMM was better at detecting a shadow.

Figure 2 shows the overview of the estimation method. First, several microscopic images showing both the micropipette and its shadow were collected by slightly changing the micropipette’s position and lighting conditions. Then, ground truth images, which one of the authors of the present work manually segmented by observation, were created for each microscope image, and its components (i.e. the micropipette, shadow, and background) were labeled accordingly. For easier visualization, the instrument, the shadow, and the background