An Augmented Reality Assistance Platform for Eye Laser Surgery*

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Abstract—This paper presents a novel augmented reality assistance platform for eye laser surgery. The aims of the proposed system are for the application of assisting eye doctors in pre-planning as well as providing guidance and protection during laser surgery. We developed algorithms to automatically register multi-modal images, detect macula and optic disc regions, and demarcate these as protected areas from laser surgery. The doctor will then be able to plan the laser treatment pre-surgery using the registered images and segmented regions. Thereafter, during live surgery, the system will automatically register and track the slit lamp video frames on the registered retina images, send appropriate warning when the laser is near protected areas, and disable the laser function when it points into the protected areas. The proposed system prototype can help doctors to speed up laser surgery with confidence without fearing that they may unintentionally fire laser in the protected areas.

I. INTRODUCTION

Retinal laser therapy is the mainstay treatment in many retinal pathologies, e.g. pan retinal photocoagulation (PRP) for ischemic retinopathy, focal and grid lasers for maculopathies associated with diabetes mellitus and branch retinal vein occlusion, as well as photodynamic therapy (PDT) and feeder vessel therapy (FVT) in age-related macular degeneration (AMD). Most current laser machines are manually-operated and based on clinical judgment or visually transposed from marked angiogram. There is however a lack of precise demarcation of areas to be lasered. In focal/grid laser, guidelines for laser recommend that laser spots can be applied up to 300μm of the fovea center. However, inadvertent fovea burn and excessive burns in areas of ischemic maculopathy, especially in the presence of severe macular edema and staphyloma where parallax errors misaligning the apparent position of the fovea often occur, can result in irreversible scotomas [1].

In PDT and FVT, localization of abnormal choroidal vessels is based on manual demarcation from the indocyanine-green angiogram (ICGA). However errors can occur due to image resolution and manual marking errors. Likewise, PRP is based on clinical judgment and may result in excessive laser treatment, causing unnecessary destruction of healthy retina and permanent visual loss, or inadequate laser treatment causing disease progression. In addition to the imprecision of current laser treatments, current laser machines are also limited by the operator’s response time. Laser procedures are usually performed under topical anesthesia. Eye movements can still occur even with the aid of a fixation lights and complicated by the presence of multi-spot light flashes (e.g. in Pascal laser). As the ‘eye-foot’ response time (0.4-0.5s) is much slower compared to the minor saccades of the eye (40-150Hz), fovea burns can occur during macular laser [2].

Diabetic macular edema (DME) is the leading cause of blindness among diabetics and occurs in 0.85-12.3% of diabetics depending on the type and duration of diabetes. Worldwide prevalence of DME is 15.7% and prevalence of visual impairment due to DME is 2.56%. Laser is still the most frequently used treatment. There are about 93 million diabetics and 21 million with DME worldwide [3]. AMD is also increasing in worldwide aging population. Pooled prevalence estimates of early and late AMD in Asians aged 40-79 years are 6.8% and 0.56% respectively. Polypoidal choroidal vasculopathy (PCV), the ‘Asian AMD’, comprises 23-49% of AMD around Asia. It is also increasing in prevalence and is typically treated with PDT [4]. With increasing diabetics and aging population, the demand for precise laser systems is on the rise.

II. RELATED WORKS

Current state-of-the-art systems such as Navilas [5] and PASCAL Streamline 577 [6] are primarily manually operated laser system. The surgeons still need to be completely focused and take extra precaution not to fire the laser at foveal tissues whose destruction are irreversible and could render permanent scotomas. A navigated retinal laser system (Navilas, OD-OS) [5] is a novel non-contact automated platform that integrates a 532nm laser with digital imaging. It allows pre-planning and demarcation of selected laser areas. However there is still a need to manually locate each microaneurysm, and the procedure is fully automated with a preselected power. As such, there may be inadequate or excessive power used in areas of unequal edema. The main unmet needs of most commercial laser systems are:

- Inability to automatically and precisely demarcate the “no-go” areas (e.g. macula or optic disc areas) for laser treatment;
- Need for a multi-modal imaging overlay to assist the surgeon in deciding areas of treatment (based on fundus and angiogram e.g. FFA, ICGA, and OCT imaging);
- Need for an automated system with a warning signal (e.g. laser cut-off, alarms) when laser approaches or enters a marked area or “no-go” zone;

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• Need for human element to maneuver and guide laser.

III. PROPOSED SOLUTION

The goal of our proposed solution is to develop and validate a system that can assist in pre-planning of laser treatment as well as react and respond during a laser treatment surgery so as to ensure better surgical outcomes for the patients. The specific aims include: (1) develop and test a clinically viable prototype; (2) clinical validation of the system for live surgery. To achieve specific aims, we developed algorithms to register multi-modal images; demarcate protected areas within the retinal; register and track slit lamp images from the live surgery; sound appropriate warning alert when the laser is near protected areas; and disable the laser function when it points into the protected areas.

Our main contribution is a prototype of an augmented reality assistance platform consisting of algorithms for multi-modal image registration, automatic optic disc and macula segmentation, and video tracking that are useful for:

- Assisting eye surgeons during live surgery.
- Coupled with multi-modality imaging and pre-procedure planning, the surgeon will be more confident in targeting the specific and precise areas for treatment, as well as to avoid the ‘no-go’ protected zones.
- Providing better surgical outcomes for the patients.
- Treatment is targeted compared to current manual visual demarcation and surgeons are better able to treat affected and abnormal areas and vessels.
- Reducing the risks of causing permanent scotomas to patients’ fovea tissues and unnecessary damage to healthy retina. Using multi-modal image-guided treatments, surgeons can avoid sensitive fovea tissue in macular laser and preserve healthy retina in PRP. Warning signals and emergency laser cut-offs act as a secondary insurance against surgical mishaps by preventing inadvertent damage during sudden eye movements.

A. Solution Overview

The diagram shown in Fig. 1 illustrates our proposed application framework. First, color fundus image(s) and fluorescein angiographic image(s) are selected as inputs into the system. Our proposed system will then perform multi-modal image registration of the color fundus image and the fluorescein angiographic (FA) image. If there are multiple color fundus images, our system will also register the multiple color fundus images. These registration information will then be stored in the system. Then, the optic disc and macula regions are automatically detected by the system and labelled as “protected regions”. Thereafter, the user can manually mark any additional sensitive regions as “protected regions” (if necessary).

During the laser treatment operation, slit lamp video is captured by the system. We perform a one-time initialization to register a slit lamp video frame to the reference color fundus image. Based on the registered slit lamp video frame, tracking process is then started and the location reporter will be able to track the user’s current field of view which decides the firing zone of the laser. The sensitive region protector will alert the user when his firing zone is close to the protected regions. When the firing zone lies within the protected area, the sensitive region protector will turn off the laser to prevent any potential harm to the patient. More details on the above algorithms are provided in the following sections.

Figure 1. Proposed application framework.

B. Multi-Modal Image Registration

In the multi-modal image registration stage, our proposed algorithm will automatically register fluorescein angiographic (FA) image to color fundus image. Here, we proposed a robust approach for multimodal retina image registration. We first extract feature points using the Scale-Invariant Feature Transform (SIFT) algorithm [7]. Then, we estimate the Partial Intensity Invariant Feature Descriptors (PIIFD) [8] centered on the SIFT features. Thereafter, we perform a putative feature point matching using the nearest neighbor criterion on the PIIFD descriptors. Next, we perform an outliers’ elimination process to prune putatively matched feature points using our proposed robust outliers’ elimination technique that enforces an affine transformation geometric constraint.

The outliers’ elimination and affine transformation parameters’ estimation are achieved using our proposed adapted Least Trimmed Squares (LTS) coupled with iteratively reweighted least squares method. The original LTS estimate [9] which minimizes the sum of the least-trimmed-squared residuals is given by:

$$\hat{\Theta} = \text{arg min}_{\Theta} \sum_{i=1}^{n} \rho_i(x)$$

where $\Theta$ is the set of model parameters, $x \in R$, $R$ being the neighborhood used for the transformation computation, $\hat{r}_i <=…<= \hat{r}_r$ are the ordered squared residuals, $n$ is the total number of data in the dataset, and $h$ denotes the $h^{th}$ ranked residual above which the rest of the residuals representing $(n-h)$ will be trimmed (i.e. removed from consideration in the estimation of the model parameters).
An affine transformation model that describes the affine transformation of a point \( x = (x, y)^T \) to \( u = (u, v)^T \), in the \( x \) and \( y \) directions, can be defined as:

\[
u(x, \Theta) = Ax + b
\]  \( (2)\)

where \( A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \) and \( b = (b_x, b_y)^T \), and we can denote the transformation parameters as: \( \Theta = (a_{11}, a_{12}, a_{21}, a_{22}, b_x, b_y)^T \). Let the residual in modelling the transformation (with transformation parameters \( \Theta \)) at a point \( x \) be \( r(x, \Theta) \), where:

\[
r(x, \Theta) = \left \| u(x, \Theta) - u \right \|.
\]  \( (3)\)

Given a data set of \( n \) observations, the algorithm repeatedly draws \( m \) sub-samples each of \( p \) different observations from the data set using a Monte-Carlo technique, where \( p \) is the number of parameters in the model (\( p = 3 \) for the affine transformation model). For each sub-sample, indexed by \( J \), \( 1 \leq J \leq m \), the corresponding parameters \( \hat{\Theta}_J \) are estimated from the \( p \) observations. In addition, the sum of the least trimmed squared residuals, denoted by \( M_J \), is also determined, where:

\[
M_J = \sum_{j=1}^{J} r(x, \hat{\Theta}_j)^2.
\]  \( (4)\)

The LTS solution is the \( \hat{\Theta} \) for which the corresponding \( M_J \) is the minimum among all the \( m \) different \( M_J \)s. Thereafter, we use our proposed iteratively re-weighted least squares procedure to iteratively estimate the final affine transformation parameters and also obtain the final robustly matched feature points with outliers eliminated (see Fig. 2). Finally, we perform image registration by transforming one of the multi-modal image pair using the estimated affine transformation model. We compared our proposed approach with the original PIIFD approach and found that our proposed approach significantly outperforms the original PIIFD approach when tested on the same dataset.

![Figure 2. (left) Putative matches; (right) Matches with outliers eliminated.](image)

The above multi-modal image registration process is used during the laser treatment pre-planning phase. This will allow eye doctors to plan treatment on both types of images simultaneously by overlaying and/or fusion.

C. Automatic Demarcation of Optic Disc and Macula

In our previous work, we have developed several technologies that can be integrated into this application, including the optic disc detection, macular detection, vessel junction extraction [10, 11]. We used techniques developed in [10] to automatically detect the optic disc and macula region. In the disc detection, regions corresponding to top percentile of the grayscale intensity are selected as candidates. Constraints such as eccentricity and size are used to select the best candidate. The center of the selected candidate region is used as a seed for a region growing technique to obtain the optic disc. Using the optic disc center as a point of reference and the side of the eye for orientation determination, a region of interest (ROI) around the typical macula location is extracted. Using data from prior data, we statistically determined the average unsigned distance of the macula, along with the range of variation.

D. Manual Marking of Additional Regions

In this phase, the doctor could use our application system to manually mark additional regions as protected regions on the reference fundus image(s) in addition to reviewing the previous automatically marked protected regions. Our developed application tool allows the doctor to have several options to overlay the FA image onto the fundus image and vice versa, as well as several different image fusion modes for better and clearer viewing and diagnosis of eye diseases from these retina images. The doctor could also use these tools to guide him to mark the surgery regions which he/she intends to apply laser treatment.

E. Registration of slit lamp video frame to reference fundus image

During the initialization phase prior to laser surgery, the system performs an initialization of key slit lamp video frame to the reference color fundus image. The processes are as follow:

- The slit lamp video frame is extracted from the slit lamp video in real-time.
- The retina region is then registered to the fundus image.
- The masked retina region is then registered to the reference color fundus image.

The processes to register the slit lamp video frame to the reference color fundus image are as follow:

- SIFT feature points [7] are extracted from slit lamp video frame and reference fundus image. (Note that for computational efficiency, we extract the feature points from the reference fundus image in advance during the pre-surgery stage and store them for use here).
- SIFT keypoints’ matching are performed [7].
- Outliers’ elimination step similar to our multi-modal registration stage is performed to obtain only the correctly matched points (See Fig. 3). Note the difficulty in outliers’ elimination here because of the very large number of outliers present. Nevertheless, our proposed approach, being able to handle up to 90% of outliers, works well here.
- Slit lamp video frame is registered to fundus image.
- Tracking of slit lamp video frame on the reference fundus image is then performed (see next section).

![Figure 3. (left) Putative matches; (right) Matches with outliers eliminated.](image)
In order to track the difference between two frames, we first identify well-textured features and calculate their corresponding optical flow in each new image using a two-frame gradient-based method named Lucas and Kanade [12], also known as sparse optical flow. Optical flow is a registration method that provides a measure of the apparent motion within a sequence of images. It calculates the displacement vectors of individual features rather than tracking all of the pixels within a frame and rendering a full motion vector field. The method uses gradient information obtained from consecutive frames to search along the optimal path for a region that best matches the desired feature. The displacement vector is updated iteratively until it converges to a match with a sufficiently small error, or else it will diverge and fail to locate the targeted feature in the current frame. Features that cannot be registered in a new frame are eliminated and replaced by good features nearby. Fig. 4 shows an example of the detected optical flow within two frames.

![Figure 4. Optical flow within two frames. (a) and (b) are the two frames and (c) is the optical flow result on the image overlapping of (a) and (b).](image)

F. Tracking of slit lamp video on reference fundus image

During the tracking stage, our system will track the slit lamp video frame on the reference color fundus image. The reference fundus image is coded with protected zones etc. (during the surgery pre-planning stage). Whenever the laser is near the protected areas, appropriate warning will be sent. Whenever the laser points into the protected areas, red-alert warning will be sound and the laser firing function is disabled to prevent any mis-firing. In doing so, our proposed system is able to help doctors to speed up laser surgery with confidence without fearing that they may accidentally fire laser within the danger zones, such as the macula and optic disc regions.

Fig. 5 shows a screen-shot of current GUI display of our proposed prototype system. On the right shows the current slit lamp video frame, while on the left shows the reference fundus image with protected areas (marked in green) and the surgery areas (marked in blue). The location of the center of the tracked slit lamp video frame (marked as a blue cross) is also augmented onto the reference fundus image.

![Figure 5. Prototype display of proposed application system.](image)

G. Early Warning and Protection during laser surgery

During the tracking stage, our system was approved by the Institutional Review Board.

In this paper, we propose a novel augmented reality assistance system for the application of eye surgical assistance. Here, we propose a novel robust outliers' elimination technique for significantly improved multimodal image registration and also incorporate our prior techniques for optic disc and macula segmentation. We also developed technique for registration of slit lamp video frame to fundus image and integrated prior technique for video tracking. We show how our proposed system prototype can assist eye doctors in laser treatment pre-planning as well as provide guidance and protection during laser surgery.

**REFERENCES**


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1 The experimental procedures involving human subjects described in this paper were approved by the Institutional Review Board.