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Motion detection and compensation in infrared retinal image sequences

J. Scharcanski[a,*], L.R. Schardosim[a], D. Santos[b], A. Stuchi[b]

[a] Instituto de Informática e Programa de Pós-Graduacão em Engenharia Elétrica, Universidade Federal do Rio Grande do Sul, Caixa Postal 15064, 91501-970 Porto Alegre, RS, Brazil
[b] Opto Eletrônica S.A., Rua Joaquim A Ribeiro Souza 1071, São Carlos 13563-330, Brazil

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ABSTRACT

Infrared image data captured by non-mydriatic digital retinography systems often are used in the diagnosis and treatment of the diabetic macular edema (DME). Infrared illumination is less aggressive to the patient retina, and retinal studies can be carried out without pupil dilation. However, sequences of infrared eye fundus images of static scenes, tend to present pixel intensity fluctuations in time, and noisy and background illumination changes pose a challenge to most motion detection methods proposed in the literature. In this paper, we present a retinal motion detection method that is adaptive to background noise and illumination changes. Our experimental results indicate that this method is suitable for detecting retinal motion in infrared image sequences, and compensate the detected motion, which is relevant in retinal laser treatment systems for DME.

1. Introduction

Sub-retinal or pre-clinical pathology is challenging to observe and quantify *in vivo*[1]. Sub-retinal pathology in diabetic macular edema (DME) is one of the important causes of visual loss in developed and developing countries [2]. Histopathological studies of human eyes indicate that there is a deposition of material in the layers beneath the retina [3–5]. Also, there is a redistribution of melanin in the retinal pigment epithelium, as sick cells shed their melanin and neighboring cells take it up [6]. Choroidal new vessels can form, which presents a severe risk for vision loss, making retinal imaging measurements a necessity in the evaluation of such cases.

However, neither small deposits nor early changes are observable with standard clinical methods. Near infrared imaging is well-suited for investigating sub-retinal structures, because infrared images can reveal details of most fundus features [7]. Also, infrared imaging is preferred for sensing pathology since it is less aggressive to the patient retina. Besides, infrared imaging detects pathology despite the presence of hemorrhage or cataract, that may be undetected in other *in vivo* studies (such as angiographic dye) [1]. A difficulty with the fundus camera to provide useful infrared images can be attributed to the failure to separate reflected and scattered light, since infrared light is less absorbed than visible light, and thus may scatter over longer distances. Consequently, infrared fundus images often are noisy and present low detail definition. Therefore, infrared eye fundus images of static scenes taken at different time instants (i.e. infrared image sequences), tend to present pixel value fluctuations in time. Also, such images can present substantial changes in background intensity because even small retina movements may cause the infrared light scattering in the retina to change.

The observable clinical signs of DME include microaneurysms, dot and blot hemorrhages, exudates and intra-retinal microvascular abnormalities (IRMA), and these signs may evolve in time. It is well known that early detection can enable timely treatment minimizing further deterioration of the patient visual acuity [8]. Unfortunately, in some cases, DME tends to evolve, and in such cases laser based treatments often are used to avoid further visual acuity deterioration [9].

Nowadays, the technology for retina infrared imaging and laser treatments still is evolving. Particularly, yellow lasers have been found important in focal laser photocoagulation (around 586 nm), a common laser technique for the treatment of DME, and has been used as a complement to the administration of anti-VEGF ('Vascular Endothelial Growth Factor') drugs [4]. Usually, an expert selects the lesion areas to be treated by laser interactively, trying to avoid DME to spread in those areas. However, retina voluntary (or even involuntary) movements may disturb the laser treatment, and healthy areas may also be hit, further degrading the patient visual acuity [9]. Compensating eye movements during the laser treatment minimizes the chance of inadvertent burn placement, which is particularly important when treating close to the fovea [3]. Therefore, eye motion detection and eye motion compensation are important

* Corresponding author. Tel.: +55 5133087128.
E-mail address: jacobs@inf.ufrgs.br (J. Scharcanski).

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in DME laser treatments. In fact, we propose a method to stop the laser treatment when retina movements are detected, compensate the detected motion, and then resume the laser treatment when the retina is static again. Therefore, retinal motion detection and compensation are important issues for the successful laser treatment of DME.

A brief overview of a laser treatment system is presented here to contextualize our work. The system components are: (a) imaging system, (b) optical viewfinder, (c) aim beam laser, (d) main laser, and (e) central controller. The physician positions the aim beam laser using the optical viewfinder and the imaging system, which software allows to find the location of lesions that were previously detected using a fundus camera or other diagnosis equipment. The aim beam is displayed over all the treatment points, switching from one to another point. When the physician has the aim beam in the correct position, the laser treatment starts. The points are treated one by one, until finishing or until the process is halted by the physician or automatically. During aim positioning and treatment, the tracking system adjusts the laser position to compensate small eye motion, corresponding to less than 50 μm. If a larger retinal motion is detected, the laser is immediately stopped, as a safety system. The process is restarted in the task of positioning the aim beam and the treatment resumes.

As discussed above, retinal motion detection and compensation in infrared imaging are challenging. In this work, we wish to detect retinal motion in adjacent frames of infrared retinal video sequences, and estimate a motion compensation robust to specific spatial locations where the adjacent frames differ (e.g. noise or imaging artifacts). Retinal image registration is a related problem for which a great number of methods have been developed, and often these methods are based on the detection of local features such as retinal vessels or other salient features. However, fast and accurate retinal image registration is still a challenging problem [10,11]. Besides, retinal image registration methods are mostly used for comparing retinal images in order to find local alterations (e.g. in case follow up), which is out of the scope of this work. Nowadays, there are few studies on infrared retinal image sequences. A method for retinal motion detection and compensation on color fundus image sequences was proposed by Ober et al. [12]. Their method uses high resolution color eye fundus images, while in our work we use lower resolution infrared video sequences. In this paper we do not compare retinal imaging modalities, and the focus of our work is on algorithms for retinal motion detection and compensation on infrared retinal image sequences. Also, it shall be observed that Ober et al. [12] emphasize the treatment time and not the obtained motion detection and compensation accuracy, and they do not present data that allows a quantitative comparison with our work [12]. Other researchers have approached the problem of retinal motion detection and compensation using adaptations of known motion detection methods, such as block matching [13] or KLT/SIFT [14]. In fact, if there is no distortion between neighboring frames, correlation potentially could be used for retinal motion detection and compensation. However, such methods usually are not robust to the noise and illumination artifacts commonly found in infrared retinal imaging.

In this paper, we present a new retinal motion detection and compensation method for infrared video sequences, which is adaptive to background noise and illumination changes. Our approach relies on global statistical information instead of relying on local information (like vessels or salient features), since in infrared video sequences these local features are time consuming to compute and can be misleading due to noise and artifacts. These infrared image sequences usually are noisy, do no contain color information and have lower resolution than other retinal imaging modalities (e.g. color fundus images). Therefore, vessels and other salient features (e.g. corners) are not easily tracked since they tend to vanish or be confused with artifacts along the video sequence (e.g. vessels boundaries often fragment, and salient features tend to vanish or be confused with artifacts). Our preliminary experimental results indicate that this method potentially can detect retinal motions and compensate them in infrared image sequences, helping to improve the reliability of laser treatment systems for DME. This paper is organized as follows. Initially, our motivation is presented in Section 1. Next, our motion detection and compensation approach is described in Section 2, and our experimental results are discussed in Section 3. Finally, our conclusions are presented in Section 4.

2. Retinal motion detection and compensation in infrared image sequences

Ideally, eye fundus infrared video sequences show a static retina, and not much change is expected from frame to frame (except for noise). In practice, adjacent frame dissimilarities indicate local changes, suggesting retinal motion. Nevertheless, trivial motion detection methods (e.g. pixel differences) do not perform well in this case, because such infrared image sequences are noisy and illumination scattering may vary (see Section 1). Motion detection in retinal infrared sequences should be robust to such artifacts, and we propose an adaptive approach based on information theory, as detailed in Section 2.1. However, there are a number of situations in infrared retinal image sequences where local frame dissimilarities may be confused with actual retinal motion (e.g. blinking, out of focus images, etc.), and such situations must be detected as inconsistent. In this work, we also detect inconsistent retinal motion situations as described in Section 2.2. Our proposed motion compensation approach is described in Section 2.3, and compared with other two methods in Section 3.

2.1. Retinal motion detection

The background illumination may vary substantially in infrared image sequences, but the local image gradient magnitudes are less susceptible to such variations than the image gray levels. In other words, let $I(t)$ be an image (frame) at time t of an infrared image sequence, and the local gradient magnitude be $|\nabla\vec{I}(t)|$. Let us assume that $I(t)$ and $I(t+\Delta t)$ are captured from a static retina at times t and $t+\Delta t$, and the local image gradients are $\nabla\vec{I}(t) = \left[\frac{\partial I(t)}{\partial x}, \frac{\partial I(t)}{\partial y}\right]^T$. Since $\frac{\partial I(t)}{\partial x} = \frac{\partial (I(t)+a)}{\partial x}$ and $\frac{\partial I(t)}{\partial y} = \frac{\partial (I(t)+a)}{\partial y}$, if the background illumination changes linearly and $I(t+\Delta t) = I(t)+a$ (where a is a constant), then $|\nabla\vec{I}(t)| = |\nabla(I(t)+a)|$. Therefore, the local gradient magnitudes are not affected by constant gray level scaling (i.e. are invariant to background illumination changes approximated as linear scalings).

Since the retinal infrared images are noisy, the local gradient magnitudes $|\nabla\vec{I}|$ also are contaminated by noise, and noise may be non-stationary in these images. Therefore, we need a robust method for measuring adjacent frame similarity. In this work we use an information theory approach, since precise prior noise estimates or illumination variation are not needed in this case, and this approach can accommodate virtually any probability distribution for the image artifacts. In this case, the $X = |\nabla\vec{I}(t)|$ and $Y = |\nabla I(\vec{t}+1)|$ statistics can be estimated directly from the gradient magnitude test data. In order to measure inter-frame dissimilarities, we need generic statistical distribution measures, and in this work we considered different information theoretic measures such as mutual information $MI(X, Y)$, joint entropy $H(X, Y)$, Universal Metric $D(X, Y)$ and Conditional Entropy $HC(X, Y)$. To better explain how