Optics Communications 313 (2014) 321–328

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Enhancing retinal images by extracting structural information

G. Molodij [a,b,*], E.N. Ribak [b], M. Glanc [a], G. Chenegros [a]

[a] LESIA-Observatoire de Paris-Meudon, CNRS, Université Pierre et Marie Curie-Paris 06, Université Paris Diderot - Paris 07, 5 Place J.Janssen, 92190 Meudon, France

[b] Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel

ARTICLE INFO

Article history:
Received 24 March 2013
Received in revised form
13 September 2013
Accepted 2 October 2013
Available online 22 October 2013

Keywords:
Image processing
Image quality assessment
Perceptual quality
Restoration

ABSTRACT

High-resolution imaging of the retina has significant importance for science: physics and optics, biology, and medicine. The enhancement of images with poor contrast and the detection of faint structures require objective methods for assessing perceptual image quality. Under the assumption that human visual perception is highly adapted for extracting structural information from a scene, we introduce a framework for quality assessment based on the degradation of structural information. We implemented a new processing technique on a long sequence of retinal images of subjects with normal vision. We were able to perform a precise shift-and-add at the sub-pixel level in order to resolve the structures of the size of single cells in the living human retina. Last, we quantified the restoration reliability of the distorted images using an improved quality assessment. To that purpose, we used the single image restoration method based on the ergodic principle, which has originated in solar astronomy, to deconvolve aberrations after adaptive optics compensation.

1. Introduction

Early detection of retinal pathologies can be performed by non-invasive observation of the retinal tissue to a cellular level. The ability to resolve micron scale structures in the retina can help better understand the biophysical and vision processes of the retina [1,2], and can provide early diagnosis of retinal diseases. Adaptive optics systems, initially developed for astronomy, can compensate for real-time dynamic aberrations of the eye in order to improve the resolution of images of the retina [3–6]. However, for improving resolution, the pupil has to be dilated, and as a consequence, primary and high-order aberrations are added to the ocular optics, resulting in a blurry image and suffering from a low signal-to-noise ratio. In many cases adaptive correction is partial [7]: the images of the eye are not yet limited by diffraction and current retinal imaging offers insufficient resolution, the reasons for which might also be saccades (rapid eye motion). There exist computational imaging algorithms that are able to superresolve sets of images [8–12]. Still, adaptive optics is not always fully successful on all patients and is not always able to reach the theoretical resolution. Thus we seek to supplement the partial results of adaptive optics with image processing to improve the final image quality. Their interpretation is often difficult without a proper deconvolution processing.

Because of the level and complexity of the aberrations in the eye, computational imaging algorithms cannot improve the image significantly, since they are based on deconvolution of the aberration operator from the high-resolution image, but the time dependence of this operator is not trivial [13]. The proper estimation of the image quality and of the reliability of the deconvolution is certainly the most difficult task to perform. High resolution details clearly arise on images after the restoration with the higher contrast, but are these true details or numerical artifacts? The simplest and most widely used full-reference quality metric is the mean squared error, computed by averaging the squared intensity differences of distorted and reference image pixels, along with the related quantity of peak signal-to-noise ratio. These are appealing because they are simple to calculate, have clear physical meanings, and are mathematically convenient in the context of optimization. But they are not very well matched to perceive visual quality [14–16].

Objective methods for assessing perceptual image quality have traditionally attempted to quantify the visibility of errors between a distorted image and a reference image using a variety of known properties of the human visual system [17–19]. In the matter of sensation of light, we have to deal with quality as well as quantity. The 19th century studies of psychophysicists Weber [20] and Fechner [21] on the response of the human eye to light state that this response is logarithmic: that is, that the eye essentially takes the logarithm of the incoming optical signal.

* Corresponding author at: LESIA-Observatoire de Paris-Meudon, CNRS, Université Pierre et Marie Curie-Paris 06, Université Paris Diderot - Paris 07, 5 Place J. Janssen, 92190 Meudon, France. Tel.: +33 145077909; fax: +33 145077959.

E-mail addresses: guillaume.molodij@obspm.fr (G. Molodij), eribak@physics.technion.ac.il (E.N. Ribak), marie.glanc@obspm.fr (M. Glanc), guillaume.chenegros@obspm.fr (G. Chenegros).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.10.011

In this paper, we present an image processing algorithm for resolution enhancement of retinal images. The novelty in the suggested method is the ability to significantly improve the resolution of an ensemble of poor quality retinal images using a quality assessment based on the degradation of structural information. A precise shift, select and add process is performed on a long sequence of retinal images, using image quality assessment based on the Weber–Fechner criterion. In order to evaluate the restoration reliability using the improved quality assessment, we applied successfully a restoration technique based on an estimation of the maximum of the Laplacian of the irradiance, in which an isotropic reference is obtained from the analysis of details inside the isoplanatic patch using the ergodic principle [22]. This deconvolution method arose in the cases of extended fields-of-view such as the Sun, where the texture does not often present punctual references to estimate the aberrations, but rather high resolution details that can be exploited for that purpose.

We recall briefly in Section 2 the theoretical background of the Weber–Fechner criterion we used to determine the image quality assessment, and to perform a precise shifting, selection, and addition. In this section, we present also some improvements of the criterion to quantify the visibility of errors between the distorted image and the reference image. Section 3 presents the result on real data and the different steps of the enhancement processing. Last, in Section 4, we discuss the application of this study in the fields of optics and imaging in astrophysics in order to improve the visualization of the retina at very high spatial resolution, and to implement methods for high-resolution retinal imaging purposes.

2. Weber–Fechner assessment

Most perceptual image quality assessment approaches proposed in the literature attempt to weight different aspects of the error signal according to their visibility, as determined by psychophysical measurements in humans or physiological measurements in animals. This approach was pioneered by Mannos and Sakrison [23]. The development of an image processing algorithm for resolution enhancement depends on our capability to assess the image quality. Under the assumption that human visual perception is highly adapted for extracting structural information from a scene, we use an alternative framework for quality assessment based on the analysis of the structural information [19]. Most images are highly structured in the sense that each pixel is dependent on its neighboring pixels. This dependence provides an information on the structure of objects in a scene. In this approach, we are more interested in comparing the structures between the corrected and the degraded images. After all, measurements of the image structural information give a better assessment of the corrugation perception than the estimation of errors between images. In our approach, the image quality assessment is then determined by the modification of the structural information. To fulfill this purpose, we propose to improve the Weber–Fechner criterion it takes into account the logarithmic sensitivity of eyes in terms of the light and the structural information in the image.

The image quality measurement has to take into account not only the absolute value between two pixels but also the mean values. Our Weber–Fechner quality criterion is Qc, the relative distance between restored $I_r(i,j)$ and corrugated $I_c(i,j)$ pixels

$$Qc = 20\ \mathrm{Log}_{10} \frac{Max[I_r^2(i,j)]}{\delta_d}, \qquad (1)$$

with

$$\delta_d = \frac{1}{IJ} \sum_{i=0}^{I} \sum_{j=0}^{J} \frac{|I_r(i,j) - I_c(i,j)|}{I_r(i,j) + I_c(i,j)}. \qquad (2)$$

This quality criterion Qc drops to zero as the difference increases between the two images, and it tends to infinity as the two images become similar. We show below how this quality criterion was implemented on a long sequence of retinal images of subjects with normal vision to perform successfully a precise shift-select-and-add at the sub-pixel level.

Nevertheless, this quality criterion suffers a lack of sensitivity for images with poor contrast and the calibration remains difficult on the corrugated images. The quality criterion determined by Eqs. (1) and (2) is not able to quantify the restoration reliability of the distorted images. Stronger structural information can be characterized by the histogram of the corrugated image intensity, or by the strength of the gradients of the images. Using the dynamic range adjustment transformation from the raw image histogram to increase the contrast, Eq. (2) becomes

$$\delta_d = \frac{1}{IJ} \sum_{i=0}^{I} \sum_{j=0}^{J} \frac{[I_r(i,j) - I_c(i,j)]^2}{\mathrm{histo}(i,j)}, \qquad (3)$$

where histo(i,j) is the affine transformation (see Appendix A).

Similarly, for the gradient structured function, Eq. (2) becomes

$$\delta_g = \frac{1}{IJ} \sum_{i=0}^{I} \sum_{j=0}^{J} [\nabla I_r(i,j) - \nabla I_c(i,j)]^2, \qquad (4)$$

where the gradient is taken at half scale of the image spatial correlation.

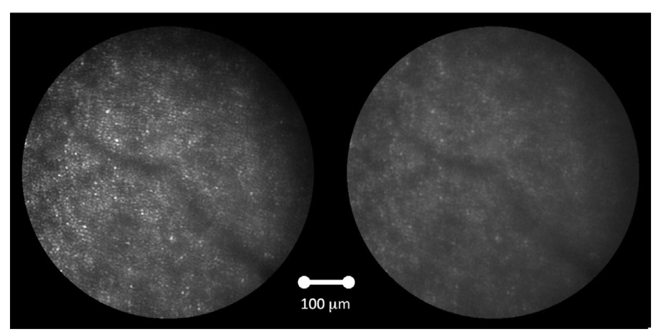

Fig. 1. Comparison between the mean processed image (left) and the best raw image (right) on data taken at the XV-XX Hospital. The r.m.s contrast value is 8.1% for the restored mean image while the value is 4.1% for the best raw image.

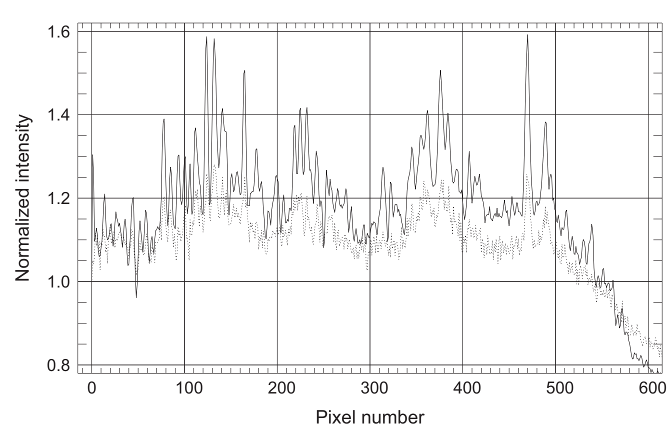

Fig. 2. Comparison of intensity profiles along the same selected lines across the retina image after the complete processing (plain line) and before the processing on the best raw image (dashed-line) of Fig. 1.