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# Enhancing retinal images by nonlinear registration

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ABSTRACT

Being able to image the human retina in high resolution opens a new era in many important fields, such as pharmacological research for retinal diseases, researches in human cognition, nervous system, metabolism and blood stream, to name a few. In this paper, we propose to share the knowledge acquired in the fields of optics and imaging in solar astrophysics in order to improve the retinal imaging in the perspective to perform a medical diagnosis. The main purpose would be to assist health care practitioners by enhancing the spatial resolution of the retinal images and increase the level of confidence of the abnormal feature detection. We apply a nonlinear registration method using local correlation tracking to increase the field of view and follow structure evolutions using correlation techniques borrowed from solar astronomy technique expertise. Another purpose is to define the tracer of movements after analyzing local correlations to follow the proper motions of an image from one moment to another, such as changes in optical flows that would be of high interest in a medical diagnosis.


## 1. Introduction

High-resolution imaging of the retina has significant importance for science: physics and optics, biology, and medicine [1–3]. Early detection of retinal pathologies can be performed by noninvasive imaging of the retinal tissue to a cellular level. A method of gathering knowledge about healthy and diseased organs, tissues, and cells is the integration of complementary information from images of these objects, obtained by different modalities, different image acquisition techniques, or different object preparation procedures. A valuable task in the integration of image information is image registration by which images, containing the complementary information, are brought into the best possible spatial correspondence with respect to each other.

The eye is difficult to observe because it presents static and chromatic aberrations. Natural fixational eye movements made by the patient during recording produce distortions that are unique in each frame. Correction for these distortions is necessary before multiple frames can be added together to achieve noise reduction or to build a mosaic image from different retinal areas. These motions include rapid jerks or saccades, slower drifts, and high frequency tremor referred to fixational eye movements [4]. The dynamic aberrations of the eye can be compensated, in real time, by an adaptive optics system [5–9]. Imaging of the human eye fundus with high resolution has gained in importance because of the possibilities offered with adaptive optics to image with near diffraction limited resolution near the fovea, resolving cone photoreceptors and ganglion cells, allowing blood cell tracking and optical slicing of the retina, and providing improved diagnostics of retinal abnormalities [10–15]. Nevertheless, the observation of abnormal cell patterns of the ill retina is accompanied by unfavorable conditions that make the analysis more difficult. Patients with severe deformities of the cornea can no longer fit in the analysis sessions because of the difficulty to focus on their retinae. Images are thus of low contrast, and difficult to interpret. The correction by an adaptive optics system is however partial and resolution of the images obtained is not sufficient [16]. To circumvent this problem, images are mosaiced from scanning by confocal lasers or optical coherence tomography. Further work, and major challenge for medical applications, should be to assess the ability of processing methods of retinal images to function in very poor conditions with a reliability rate of the highest possible standards.

In a previous study, we explored a new aspect of the analysis of image quality degradation based on structural information and we demonstrated enhanced processing of sequences of fundus images

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obtained using a commercial adaptive optics flood illumination system [17]. In the case of the retinal images considered, we process sequences of images with random translations produced by ocular saccades. The illumination component is determined from the sum of the images in the sequence as it retains information on large structures in the retina such as vessels and have to be analyzed in bad conditions for wide fields of view at the expense of the resolution. Image registration is the technique to fit an image to another image. The simplest linear transformation function is horizontal and vertical shifts. Rotation and scaling are also typical linear geometric transformations for image registration. A more general geometric transformation is the affine transformation that includes translation, rotation, scaling, shear, and their arbitrary combinations. Nevertheless, classical rigid registration techniques can only be used in limited special cases. Nonlinear image registration, or deformable template, realizes more flexible image registration that can map a straight line as a curve. The hierarchical subdivision strategy which decomposes a non-rigid matching problem into numerous local rigid transformations is a very common approach in image registration. While mutual information [18] has proven to be a very robust and reliable similarity measure for intensity-based matching of multimodal images, numerous problems have to be faced if it is applied to small-sized images, compromising its usefulness for such subdivision schemes [19]. One possible way to approach is to implement elastic registration by windowing the original images and finding local rigid transformations that are elastically interpolated into a continuous deformation field [20,21].

Fixational eye movements typically produce gaze instability of 10 or 15 arc minutes during sustained periods of attempted steady gaze [4]. Although a registration can be applied, it is better to remove the image distortions due to eye movements. Registration of successive frames taken with a moving eye can also allow for the assembly of a larger retinal image mosaic. The eye rotation together with the fact that the eye is a nonrigid structure that undergoes brutal accelerations (over 20.000 deg/s$^{-2}$ [22]) during the recording process may produce complex deformations. In an application to ocular polarimetry, Nourrit et al. [23] considered nonlinear functions (polynomials of orders 2–4) that allow taking into account torsions [24,25].

Visual object tracking is also an important image processing technique for medical diagnosis. In the image processing research community, many object tracking methods have been proposed so far [26]. The optical flow technique allows us to estimate the motion at all the pixels at each frame to visualize the motion field on the entire image [27,28]. The technique is useful to analyze not only the motion but also the proper deformation or the segmentation in the tracked field of view [29,30]. Result of object tracking, i.e., the temporal trajectory of the target, is often used for plotting a velocity map and a moving direction histogram. It is also useful to analyze some other characteristics, such as a deviation from a reference. Another function of the optical flow technique would be to evaluate the similarity or dissimilarity between two temporal patterns and of interest for health care practitioners such as the blood flow imaging [31] or the automated tracing algorithms for oximetry from dual images [32].

The selection and the re-centering of large field of view solar images is a technique which has been applied to astronomical images and is referred to local correlation tracking technique (LCT) originally dedicated to the elimination of distortions coming from terrestrial atmospheric turbulence on images of the solar granulation [33–35]. This processing method has revealed new morphological features in the solar atmosphere [36], allowing us to track motions of penumbral features and granules in order to determine flows around Sunspots [37], or around solar pores associated with the emergence of magnetic flux [38]. As a last example for the space weather forecast, the method is used in the measurement of the magnetic helicity injection [39].

Therefore, this method is able to correct aberrations due to eye movements during measurements on a basis of a nonlinear registration approach, and increase the entire field of view that can be explored at high resolution taking into account the image shifts as well as the image distortion and rotation [40–43].

Adaptive optics corrected image sequences show variations in the quality that deteriorates before and during blinks of the eye, but variations are also observed although not associated with blinks. Nevertheless, the use of a multiframe mode with a registration method to increase the signal-over-noise ratio must incorporate an image selecting step to exclude poor quality images from further processing as well as to examine the extent of the final improved image quality. For this purpose, we need a reliable measure of image quality, and many methods have been proposed for determining image quality [44–47]. In a previous work, attempts have been made to measure the quality of extended fundus images [17]. These images have less high-resolution details, and typically involve measuring the size of the edges of large anatomical features such as blood vessels [48].

In this paper, we present an image processing algorithm for resolution enhancement of extended retinal images. The novelty in the suggested method is the ability to significantly improve the resolution of an ensemble of poor quality and large field of view retinal images using a nonlinear registration method based on the LCT technique. We recall briefly in Section 2 the technique to determine the proper motion that maximizes the spatially localized cross correlation between two images of a scene separated by a sampling time shorter than the lifetime of tracers in the scene. In Section 3, we compare and discuss the different image quality assessments to determine the improvement in the field of view. Section 4 is dedicated to the result obtained with real data. 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. LCT nonlinear registration method

Registration can be broadly classified into intensity or feature based. The intensity based methods have the inconvenience of poor performance under varying illumination while feature methods are based on accurate and repeatable extraction of the features. Usually, intensity based methods are applied on retinal images which may not contain sharp information [49,47]. Nevertheless, we showed in a previous work that retinal images contain enough details to extract structural information for direct template matching, without the need to detect prominent features [17]. The simplest tracking method is the template matching-based method that needs to prepare an image of the target object as a template image. Then, the location with the highest similarity to the template on each frame is considered as a new target location. The new target location at is often searched around the previous location for forming a smooth temporal trajectory [3]. Fig. 1 shows the principal steps of the registration method borrowed from solar astronomy technique [33,34]. The proper motion can be defined as the displacement that maximizes the spatially localized cross-correlation between two images of a scene (see Appendix A). For each subfield, a two-dimensional cross correlation is computed with respect to a reference image convolved with a Marr–Hildreth filter [50] in order to overcome the discontinuities at the edges of the selected windows which are lost, especially when the windowing becomes smaller compared to the template spatial autocorrelation. This filter is analogous to the commonly used