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Comparison of image registration methods for composing spectral retinal images

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ABSTRACT

Spectral retinal images have significant potential for improving the early detection and visualization of subtle changes due to eye diseases and many systemic diseases. High resolution in both the spatial and the spectral domain can be achieved by capturing a set of narrow-band channel images from which the spectral images are composed. With imaging techniques where the eye movement between the acquisition of the images is unavoidable, image registration is required. As manual registration of the channel images is laborious and prone to error, a suitable automatic registration method is necessary.

In this paper, the applicability of a set of image registration methods for the composition of spectral retinal images is studied. The registration methods are quantitatively compared using synthetic channel image data of an eye phantom and a semisynthetic set of retinal channel images generated by using known transformations. The experiments show that generalized dual-bootstrap iterative closest point method outperforms the other evaluated methods in registration accuracy, measured in pixel error, and the number of successful registrations.

1. Introduction

Eye diseases such as diabetic retinopathy (DR), glaucoma and age-related macular degeneration (AMD), or complications of many systemic diseases like diabetes and systemic hypertension (SH), cause structural changes in the eye fundus. Early detection of the retinal changes, monitoring of their progress and risk factor analysis allow better and more cost-effective treatment as most diseases can be successfully treated if they are diagnosed early and monitored regularly (e.g., [1,2]).

Retinal imaging provides a non-invasive view into the eye and its vascular bed. It is the standard practice to screen, diagnose and monitor eye diseases. Greyscale or RGB images with high spatial resolution are commonly used in the diagnosis, complemented with more advanced eye imaging methods when necessary. To support further development of the diagnostic tools, methods for spectral reflectance measurements, especially spectral imaging of the retina, have been developed [3–8]. The aim of the development has been to improve the capabilities to detect and visualize different parts of the retina and lesions related to the eye diseases.

Depending on the imaging technology, composing high-resolution spectral images based on a set of channel images may require image registration. In [4], for example, an imaging system for capturing spectral images of the retina using a set of 30 narrow-band interference filters is presented. Changing the filters requires time, thus, the eye moves with respect to the camera and image registration is needed. The purpose of the registration is to find the geometric transformation needed to spatially align the images with each other. Manual registration by selecting corresponding points in image pairs becomes difficult and even infeasible when the number of individual channels increases, or when the image features become less salient between the images. Four example images acquired with the imaging system described in [4] using 2×2 pixel binning are shown in Fig. 1.

To solve the image alignment problem, there exists a significant body of work in the field of image registration. However, the major-

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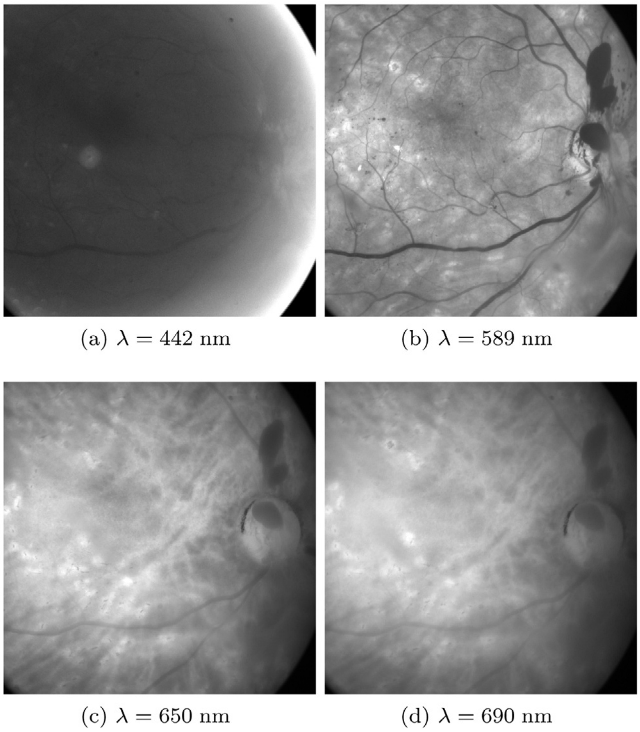

Fig. 1. Example channel images captured with the system in [4]. The images are normalised to the intensity mean of 0.5 and standard deviation of 1 for visualisation.

ity of the approaches are designed for images originating from the same imaging modality. While registration approaches designed for multimodal data exist (e.g., [9,10]), the resulting images are expected to be similar enough for feature matching. Neither of these prerequisites are necessarily true for the channel images when the difference in acquisition wavelength is large. Despite the fact that in the case of spectral retinal imaging the channel images are captured with a single modality, the image appearance varies significantly as can be seen in Fig. 1.

This paper presents a comparison of image registration approaches for composing spectral retinal images from channel images, and more generally, for aligning retinal images with significantly different visual information content. The compared methods are a well-performing subset of the methods evaluated in the preceding study [11]. As in the previous study, this paper quantitatively evaluates the methods' performance on synthetic and semisynthetic retinal image data. Here the comparison is significantly deepened by including the following subtopics: (i) the effect of different image set registration strategies on the spatial accuracy of alignment, (ii) the residual spatial inaccuracy and its effect on the spectral image quality and (iii) presentation of the evaluation results more inclusively.

2. Related work

Image registration in general and in the field of medical imaging is a widely studied problem. An example review of general image registration methods based on both features and similarity metrics has been presented by Zitova and Flusser [12]. The review includes discussion on approaches to feature detection and matching, mapping function design, and image transformation and resampling. The evaluation of registration performance of feature and area based registration methods is also discussed. More modern approaches to image registration are presented in the study by Wyawahare et al. [13].

A significant part of medical image registration literature focuses on magnetic resonance imaging (MRI), computed tomography (CT) and other radiological modalities. Maintz and Viergever [14] present an extensive review of medical image registration approaches. A significant number of the methods reviewed deal with the registration of radiological images, with methods dealing with monomodal, multimodal and modality to model registration. Hill et al. [15] review the main approaches for registering radiological images. The review presents an overview of rigid feature-based methods and intra- and intermodal (voxel) similarity-based methods. Bhatia et al. [16] present a qualitative evaluation of similarity metrics for groupwise non-rigid registration, including a novel metric. The methods are evaluated on MRI data.

A more recent review on medical image registration is the one by Markelj et al. [17]. Three classes of registration base and strategy are identified: feature-, intensity- and gradient-based methods, and projection, back-projection and reconstruction strategies. However, while the paper cites a number of other modalities, the scope of the review is limited to 3D-to-2D registration. In [18], Oliveira and Tavares describe the geometric transformations, similarity measures and optimisation methods in common (medical) registration approaches. In addition, available registration software and methods for performance evaluation are reviewed.

Deformable transformation models have been widely used in medical image registration to cope with dynamically changing organs and inter-person variation in the anatomy. Crum et al. [19] present an overview of deformable medical image registration, with the presented methods dealing mostly with radiological modalities. A number of well-known similarity measures, such as sum of squared differences (SSD), correlation coefficient (CC) and mutual information (MI) are included. Non-rigid transformation models including splines and demons are also discussed. Bhatia et al. [16] present a qualitative evaluation of similarity metrics for group-wise non-rigid registration, including a novel metric. The methods are evaluated on MRI data. Sotiras et al. [20] present a comprehensive study of recent approaches to deformable image registration. A large number of deformable registration methods, classified by the deformation models, matching criteria and optimisation approach used, are described. While not limited to the application area, the study puts an emphasis on methods dealing with the registration of medical images.

Spectral imaging typically produces images with tens or hundreds of spectral channels. Compared to the traditional three-channel red-green-blue (RGB) or single-channel grayscale images, spectral images include a superiorly vast and detailed information content encoding, for example, accurate spectral color information of an imaged object. Methods for registering spectral images have been proposed by, e.g., [21–23]. However, the papers on the registration of spectral images focus on remote sensing data which are commonly acquired from a large distance. In retinal imaging, due to the wide-angle optics and the significantly curved imaging target, the pose changes of the eye w.r.t. the camera cause warping in and distortions near the edges of the images. In addition, the penetration depth of light into the multilayered tissue of the eye fundus differs at different wavelengths which causes significant variation in the channel images.

While a large part of medical image registration literature is focused on radiological modalities, methods for registering retinal images have also been studied. As a part of their review on methods applicable to the automatic screening of diabetic retinopathy, Teng et al. [24] present an overview of feature-based registration methods and two methods that utilise the whole retinal image. The features used include matched filter responses, vessel branching points and manually marked anatomy markers. The reviewed methods were constrained to rigid transformation models. Laliberté et al. [25] quantitatively evaluate registration methods on