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Translation Histogram Based Hierarchical Algorithm for 3-D Optic Nerve Head Modeling

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Abstract

This paper describes a translation histogram based, hierarchical algorithm for automated three-dimensional (3-D) optic nerve head (ONH) modeling from stereoscopic ONH photographs. Recovering the depths in featureless region is still one of the problems in previous studies of 3-D ONH reconstruction. The proposed algorithm hierarchically optimized and modeled the peripheral ONH surface to solve this problem. The algorithm has various steps consisting of disparity detection, hierarchical surface modeling, weighted fusing, and depth calibration. Dual-registration algorithm is firstly applied to precisely detect the matching points which are then converted into disparities. The peripheral ONH surface is initialized and refined through hierarchical modeling and optimization from the disparities. The final 3-D ONH model is generated by fusing the modeled peripheral ONH surface and the depths measured from dual-registration together with the interpolation. The true depth is obtained after calibration of eye lens through the axial length information. The experimental results showed the proposed algorithm could successfully generate 3-D ONH model, and get good consistency with human expert in cup-to-disc (C/D) ratio evaluation. The algorithm indicates the potential usefulness for 3-D ONH modeling and evaluation.

Keywords

Optic nerve head; 3-D reconstruction; ONH; retina

I. Introduction

Optic nerve head (ONH) is one of the main components on the retina. Assessment of its 3-D shape is often studied for a clue of some eye diseases, such as glaucoma. Glaucoma is the second most common cause of blindness, characterized by progressive damage of the optic nerve [1]. Although various ocular imaging instruments, such as Heidelberg Retina Tomograph (HRT) and Optical Coherence Tomography (OCT), provide 3-D information and clinically useful quantitative assessment on glaucoma diagnosis and management, it is still a clinical standard and routine to perform subjective optic disc assessment using disc photos and visual field testing. Since the image acquired by HRT or OCT is not a natural color image, the technician often has difficulty of identifying the disc margin, resulting in errors of interpretation. Natural color disc photographs provide a useful reference to guide the technician in this respect. Moreover, the ONH scan by OCT is not easily reproducible due to the reason that the photographer manually locates the disc center in each scan. Stereo disc photograph has been used to document structural abnormality/changes in glaucomatous

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eyes in decades. Reconstruction of the 3-D ONH model will not only provide clinicians a clear and direct view of ONH structure, but it can also make significant improvements in subjective quantification of ONH which is generally used to evaluate the progress of glaucoma.

Little amount of information on 3-D retinal surface reconstruction was previously reported [2]-[8]. Most of them used parallel stereo configuration in which the depth is calculated from correspondences by triangular computation and the correspondence search becomes the most important task. The 3-D retinal surface reconstruction could be roughly separated into two categories: local matching and global matching (global modeling). Local matching can provide detailed information, however it may introduce some local errors. Global modeling generally optimizes the 3-D shape as a given model through the detected local matching. K. Deguchi *et al.* [2] described a reconstruction method of globally fitting the retinal surface to a sphere using wide-angle fundus images. Some methods for fundus image registration made use of the sparse bifurcations of blood vessels to globally estimate a defined transformation model [3][4]. However, the depth variation in disc region was ignored in those models, which might not be adequate for diagnosis of glaucoma. Corona *et al.* [5] introduced a local matching method, power cepstrum technique [6], for disc image registration and 3-D reconstruction. Xu and Chutatape [7] proposed a dual-registration local matching method for 3-D ONH reconstruction. Both of these local matching methods depend on local features. The reconstruction accuracy might reduce in the area without enough features. How to improve the accuracy in featureless area is still an unsolved problem.

In this paper, a translation histogram based hierarchical algorithm was proposed to model 3-D ONH and retinal surface, which extended the previous work [7] of dual-registration reconstruction. The peripheral ONH surface was initialized and hierarchically refined through re-sampled disparities computed from translation histogram. The final 3-D ONH was generated by fusing the modeled retinal surface and depths from dual-registration, which combined both the global and local information to solve the above mentioned problem.

II. Methodology

In previous studies [7], the authors have proposed a dual-registration algorithm to detect the matching points and generate the sparse disparity map. The final 3-D ONH image was obtained by interpolation. However, this local matching algorithm relies on the features on the retinal surface, where blood vessels are the most important features. The region without blood vessels may not obtain accurate matching, or even could not detect any matching. Based on the observation, the ONH region always have more features since the blood vessels flow together at that region and there are some other features such as the margin of disc. On the contrary, the region far from disc always has relatively less features. Therefore a hierarchical algorithm is proposed to model the retinal surface excluding the disc region. The algorithm uses the histogram of sparse disparities to hierarchically refine the retinal surface. The 3-D ONH modeling process has various steps consisting of disparity detection, hierarchical modeling and optimizing of peripheral ONH surface, weighted fusing, and depth calibration.

A. Disparity detection

Based on the epipolar geometry, in parallel stereo image pair, the depth is inversely proportional to the disparity between the two matching points, as shown in Fig. 1, written as $z = bf/(v_L - v_R)$, where $\mathbf{M}(x,y,z)$ is 3-D object point according to origin $\mathbf{O}$, $\mathbf{mL}(u_L, v_L)$ and $\mathbf{mR}(u_R, v_R)$ are the matching points in the left and right images respectively according to

origin $\mathbf{O}_L$ and $\mathbf{O}_R$, the term $(v_L - v_R)$ is disparity, f is the focal length of the two camera, b is the baseline which is the distance between two cameras centers. The focal length was measured to be 9.6mm and baseline was found to be 3mm for our Nidek 3Dx camera. Therefore 3-D ONH reconstruction was converted into searching the matching points to generate the disparity map and finally transform into depth map. Constraint-based dual-registration method [7] was applied on the stereo disc photos to detect matching points. Two operations, cross-correlation method and feature-based methods, were employed to detected matching points. The points with maximal correlation and with minimal feature-based difference were extracted as the best matching points for the two operations. The final matching point was the constraint-based optimal selection from the results of two operations. The detected correspondences (matching points) were saved as a sparse disparity map, denoted as $D(x,y,disp)$.

B. Retinal surface modeling

Mostly, peripheral ONH surface is close to a flat. Therefore 2nd order polynomial is enough to model the retina surface. 0th order to 2nd order hierarchical transformation models were proposed and applied to optimize the peripheral ONH surface. Using the coordinate system of the left image as the reference coordinate system, the 3-D object point denoted as $M(x,y,z)$ is corresponding to $D(x,y,disp)$, while the disparity is inversely proportional to the depth written as $disp = const / z$, $const$ is a constant measured from imaging system. The 0th order model is a horizontal flat. The hierarchical models are written as

$$\begin{cases} z=z_0 & 0^{th} \text{ order model} \\ z=ax+by+c & 1^{th} \text{ order model} \\ z=ax^2+bx+cy^2+dy+e & 2^{nd} \text{ order model} \end{cases} \quad (1)$$

In this paper, the disparity surface was computed and converted into the retinal surface. For the hierarchical computation, the surface is initialized with 0th order model and the lower level model is used as the basic disparity to generate the new, higher level model. A deformable model technique [9] was applied on stereo disc photos to segment the disc margins and measure the disc centers for both left and right images. The translation between two disc centers was used to initialize the disparity surface. Least mean square (LMS) technique was used to optimize each transformation model from all the detected correspondences on the sparse disparity map. At different model levels or different optimization iterations, the sparse disparity map is re-sampled by translation histogram for optimization. Various sample rates could be used in one model level, but must obey the top-down rule. The proposed method of hierarchical optimization of peripheral ONH surface including hierarchical modeling, optimization, top-down re-sampling of disparity map, and weighted fusion, is depicted in a block diagram as shown in Fig. 2.

C. Re-sampling disparity map by translation histogram

The sparse disparity map with the original size and all correspondences, is re-sampled with the sample rate of 2^n , $n=1, 2, \dots, N$, to generate rough-to-fine disparity maps. The whole disparity map is divided by 4×4 sub-windows, 8×8 sub-windows and so on. The disparity of the correspondences is the translation between the point in the left image and its correspondence in the right image. For each sub-window of the disparity map, translation histogram is first generated from all the correspondences inside the window. The peak of the histogram is set to be the translation of this window. All the correspondences inside the window are replaced by a single disparity located at the center of window. Therefore the original disparity map is re-sampled to the map with the size of 4×4 , 8×8 and so on. The disc

region is excluded in disparity map re-sampling, since depths inside disc region could not be modeled as a 2nd order polynomial.

D. Weighted fusion

The hierarchical algorithm only models a peripheral ONH surface, where the correspondences inside disc region are excluded in the computation. Meanwhile, dual-registration and interpolation approaches [7] could generate the 3-D retinal surface, which is more accurate in the ONH region compared with the peripheral featureless region as mentioned previously. Therefore it is reasonable to fuse these two surfaces. Let P_{surf} and P_{disc} denote the depth map from hierarchical modeling and depth map from dual-registration together with interpolation respectively, w_{surf} and w_{disc} denote the weights for these two depth maps respectively, the final 3-D ONH model is the weighted combination of these two depth maps, written as $P = w_{disc}P_{disc} + w_{surf}P_{surf}$. The weights are measured based on the location of each pixel, written as

$$\begin{cases} w_{disc}=1, w_{surf}=0 & r \leq r_0 \\ w_{disc}=\frac{r_{ref}-r}{r_{ref}-r_0}, w_{surf}=\frac{r-r_0}{r_{ref}-r_0} & r_0 < r \leq r_{ref} \\ w_{disc}=0, w_{surf}=1 & r > r_{ref} \end{cases} \quad (2)$$

where $r = \sqrt{(x - u_0)^2 + (y - v_0)^2}$ is the distance to the disc center, r_0 is the average disc radius, r_{ref} is the reference radius, which was set to be $2r_0$ in this paper.

E. Depth calibration

Based on the report in literature [2], the optical imaging system of the fundus camera can be simplified into two single lenses, one for the ocular media inside the eyeball, the other for the fundus camera. The recovered 3-D ONH model from dual-registration, considering camera lens only, is with the virtual depths. True depth can be obtained after calibration of eye lens through the axial length information. Details were described in [7].

III. Result And Discussion

63 stereo disc photographs provided by the University of Pittsburgh were tested by the proposed algorithm of hierarchical 3-D ONH modeling. All the images were resized to 256×272 pixels. One example is illustrated in Fig. 3(a)-(f) to show the whole procedures and results. Dual-registration algorithm was first applied on the stereo disc photograph Fig. 3(a) to detect the sparse disparities which were converted into sparse depth map as shown in Fig. 3(b). The dense depths Fig. 3(c) were obtained through the interpolation and smoothing. Observing Fig. 3(b), the waved shape is obvious at the peripheral ONH region, and the retinal surface is a slope but not a horizontal flat. To model the surface, the sparse disparity map was re-sampled by translation histogram following the top-down rule. The retinal surface was hierarchically modeled and optimized by the sampled disparity maps. An example of re-sampled depth map (sample rate: 4) converted from the disparities is illustrated in Fig. 3(d), while its optimized 1st order model is shown in Fig. 3(e). The final 3-D ONH model was generated by weighted fusing of dense depths and peripheral ONH surface, as shown in Fig. 3(f), where the waved shape outside disc region was greatly overcome and the detailed features inside disc region were remained. Meanwhile, the slope of the retinal surface was corrected by using the direction of the 1st order model. Cup-to-disk (C/D) were automatically measured from the computer generated 3-D ONH model and compared with the expert's assessment to indirectly evaluate the accuracy of the proposed algorithm. The correlation of C/D ratios between machine quantification and human

quantification was measured to be 0.79, which implied the accuracy of the modeled 3-D ONH.

IV. Conclusion

A hierarchical 3-D ONH modeling approach based on translation histogram has been proposed in this paper, which combined local matching and global modeling techniques. The hierarchical algorithm successfully modeled the peripheral ONH surface and corrected the slope of retinal surface. By weighted fusing the modeled surface and dense depths, the waved shape problem in the featureless region was overcome, while the detailed information inside, or close to disc region was remained. The proposed hierarchical algorithm showed potential usefulness for 3-D ONH modeling, which provided clinicians a convenient and direct 3-D visualization of ONH. It performed as well as human expert in C/D ratio evaluation. It could be an effective option for 3-D ONH evaluation, longitudinal study, measurement of the progression, by using widely available disc photographs.

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Fig. 1.
Stereo image configuration

Fig. 2.
Hierarchical 3-D ONH modeling and optimization

Fig. 3. An example of hierarchical 3-D ONH modeling. (a) Stereo disc photograph, (b) Sparse depths from dual-registration, (c) Interpolated dense depths (d) Depths from re-sampled disparity map, sample rate: 4, window size: 64×64 , (e) 1st order model of retinal surface (peripheral ONH surface), optimized from re-sampled disparity map, (f) Final 3-D ONH model, generated through weighted fusion.