PSEUDO CEPSTRUM FOR ASSESSING STEREO QUALITY OF RETINAL IMAGES

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ABSTRACT

Diabetic Retinopathy (DR) is the primary cause of visual loss in the west, although 95% of visual loss cases due to DR can be prevented if detected and treated early. Early Treatment of Diabetic Retinopathy Study (ETDRS) has been set by the National Institute of Health (NIH) to assign a severity level based on evaluation of stereo retinal images of people suffering from DR, and was described as the *Gold Standard* for early detection and treatment. To produce accurate results, the implementation of the standard depends on high resolution color stereoscopic images of the retina that meets certain quality criteria such as *clarity* & *focus*, *field definition*, and *stereo effect*. A fast and robust Image Quality Assessment (IQA) tool can is imperative to efficient and accurate disease diagnosis based on ETDRS. Specifically, this paper focuses on the *Stereo Quality* of the image pair due to its importance in the grading process, and we propose the use of the Cepstrum or Pseudo-Cepstrum filtering to develop an efficient IQA tool for assessing the stereo quality of the retinal image pair.

1. INTRODUCTION

More than *three hundred million* people between the age of twenty to seventy nine are at risk for developing diabetes worldwide at a substantial health care cost of close to *one hundred thirty five billion* dollars [1]. A recent government and private survey indicated that about one in seven American adults (more than 29 million people) have or are on their ways to develop diabetes [1]. Approximately one third of people with diabetes are at risk of losing their sight due to *Diabetic Retinopathy* (DR) [2], which makes DR the primary cause of visual loss in the west [3]. Roughly 95% of all DR related visual loss can be prevented [4] if an early diagnosis and detection took place. The National Institute of Health (NIH) has established a standard known as *Early Treatment of Diabetic Retinopathy Study* (ETDRS) [5] for diagnosing stereo retinal pair. With the use of digital retinal imaging, a routine check-up can be carried out by capturing stereo color images of predefined fields as shown in Fig. 1 [6]. The images are captured by a skilled photographer and reviewed by an expert reader who grades and assigns a severity level based on the presence of specific lesions or features.

One major technical bottleneck in current ETDRS implementation is the separation between the imaging and the grading facility. The captured retinal images need to meet image quality criteria as defined in the ETDRS protocol before sending them for grading. Thus, an automated retinal *Image Quality Assessment* (IQA) tool would reduce variability among images, so that we can enhance the imaging efficiency for photographers and improve the grading accuracy for graders. IQA as defined by ETDRS encompasses a set of criteria such as *clarity* & *focus*, *field definition* and *stereo effect* [7]. This paper focuses on stereo quality which is important in the grading and diagnosis process. Our goal is to develop and validate an automated tool for *Stereo Quality Assessment* (SQA). Such tool is expected to quantify what constitutes a good stereo pair, and produce a quick and robust way of measuring the stereo quality of the image pair. A hypothesis based on human stereopsis is suggested for SQA and tested using RDS and real stereo retinal image pair. The hypothesis specifies:

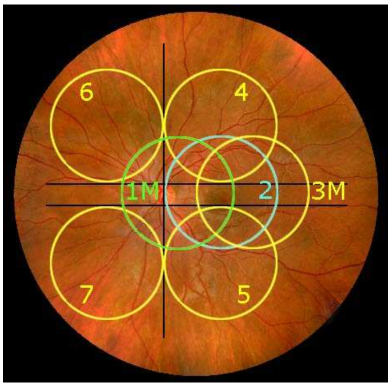

Figure 1: ETDRS fields definition. Courtesy of *ETDRS Research Group [6].*

- *A good stereo pair should have a reasonably strong horizontal disparity, and a small vertical disparity.*
- *A poor stereo pair will have either a very small or too strong horizontal disparity, or a strong vertical disparity.*

This hypothesis relates SQA with disparity measures, and thus reduces the problem of SQA to disparity estimation. Cepstrum filtering can be used as an efficient technique to find disparity between a pair of stereo images. Due to the lack of sufficiently large data sets of good and poor stereo pairs, simulation was carried out on pairs of Anaglyph *Random Dot Stereogram* (RDS) to confirm and validate our hypothesis. By adjusting vertical and horizontal disparity in RDS while viewing them using red-blue glasses on the screen, we can observe the relationship between depth perception and disparity amounts. The SQA tool would be of great assistance to the photographer in providing an instantaneous feedback regarding the quality of images and also facilitate the grading process.

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2. DEPTH IN STEREO PAIRS

Based on ETDRS standards, a professional grader can use stereo retinal image pair to identify and quantify severity levels based on certain abnormal lesions or stereo measurements, such as retina thickening, intra-retinal microvascular abnormalities (IRMA), and neovascularization (NVE). Depth information helps reveal valuable clues that are related to the presence and severity of DR. For example, Exudate and Drusen look similar in the 2D images, but they exists in the retina at different depths. Exudates does indicate the presence of DR, while Drusen is not associated with DR. By evaluating a good retinal stereo pair a distinction can be made between the Drusen which appears very deep at the level of the retinal pigment epithelium when compared to the Exudates which is usually more superficial within the outer or middle layers of the retina [5]. The above facts explain the reason behind the NIH requirements to use stereoscopic retinal pair, which are simply two separate images of the same field taken at slightly different horizontal displacement to the retina.

The projection of a 3D scene into a 2D image causes the depth information to be lost. As studied by human stereopsis, we can recover some of the depth information using a stereoscopic setup that relies on two different views. The projection of the object will be laterally displaced in the left view when compared to the right view as seen in Fig. 2, and this displacement is known as disparity [8]. Disparity can be viewed as horizontal and/or vertical coordinate shift of the same pixel or feature in the stereo pair. The brain provides a sensation of depth by fusing the two different views. According to Wheatson's [9] and Ogle's research [10] the majority of depth information is owing to horizontal disparity, while vertical disparity changes the global induced effect and could lead to a different depth perception [11]. Since disparity is related to depth, determining SQA or extracting depth from stereo pair can be reduced into disparity estimation, which can be solved by matching the corresponding points or features, subject to a set of constraints such as smoothness and uniqueness, etc [12]. Estimating disparity in stereo pair can be reduced to a matching or correspondence problem and solved using a variety of methods to derive the disparity map, such as multiresolution analysis [13], neural networks [14, 15], autocorrelation [16], wavelet [17] and biological model based on binocular cells in the visual cortex [18].

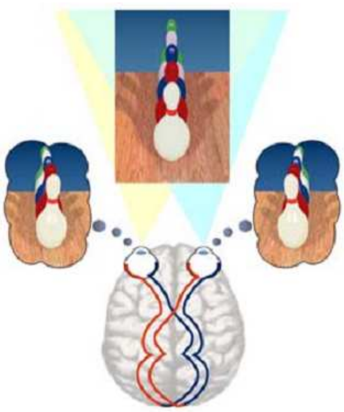

Figure 2: Depth perception from two different views. Courtesy of *Vision3D.com* [19].

3. CEPSTRUM FILTERING

From a variety of tools available to solve the disparity estimation problem, we choose Cepstrum filtering due to its simplicity and robustness. By finding correspondences, we can estimate disparity amount, similar to the registration problem [20]. Cepstrum was introduced in 1963 [21], extended to represent Homomorphic operation, and used as a non-linear filter [22]. In this work, Cepstrum links SQA with the local disparity estimation of stereo retinal image pair. Our objective is to provide a real time SQA tool where the speed of computation is an important factor.

As defined in (1), Cepstrum analysis techniques are used to examine the presence of echo in data, since convolution in the spatial or temporal domain becomes addition in the Cepstrum domain [23]. We make the simple assumption that a one of the retinal stereo pair is a duplicate copy of the other, with some distortion added to it.

$$C(p, q) = T^{-1}[\log |T[f(x, y)]|], \tag{1}$$

where T in most applications refers to the Fourier Transform. Some of the common varieties of Cepstrum mentioned in the literature are: Power, Real, Phase, or Complex Cepstrum. The Complex Cepstrum is found by omitting the absolute value. In general, the main features of Cepstrum analysis are [24]:

- Forward transformation to un-correlate the data.
- Smooth the spectrum by applying a logarithmic function.
- Use inverse transformation to return to the Cepstrum domain (spatial or temporal).

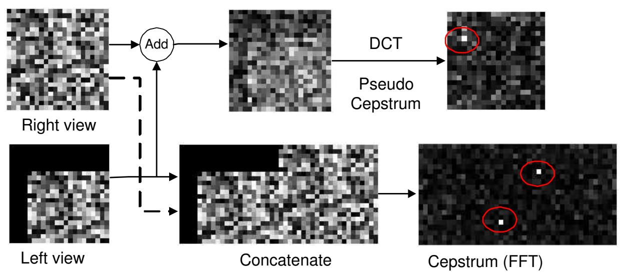

Figure 3: Upper figure shows DCT Pseudo Cepstrum applied to an added window, while the lower portion shows Cepstrum (FFT) applied to a concatenated stereo pair of Random Dot. The peak indicates the amount of shift between the two pair.

Cepstrum filtering is widely used in signal and speech processing to estimate the presence and arrival time of echo. If the signal has an echo, then the Cepstrum will have a strong peak value at a location directly related to the amount of shift or delay, as seen in Fig. 3 marked by a circle. The use of Cepstrum filtering was extended to image processing and used for visual echo detection in sequences of frames [25], texture analysis [26]. Cepstrum was used in finding disparity of two corresponding area in a stereo pair and to perform binocular stereo segmentation [27], to provide a 3D representation of biomedical images [28], and to compute depth from an image acquired by a multiple aperture camera [29]. Although the Cepstrum provides accurate estimation of disparity, the computations need to be carried out in the frequency domain, which requires phase unwrapping and complex computation. One alternative is to use a time domain method of computing the Cepstrum [30], or to use an alternative transformation instead of the Fourier transform to reduce computational complexity.

4. PSEUDO CEPSTRUM FILTERING

The term *pseudo cepstrum* was first introduced in [31], and computed using a Symmetrical Discrete Fourier Transform (SDFT) to obtain a better signal-to-noise ratio and a reduction in boundary effects. In this paper we explore alternative transformations to the FFT used in the traditional Cepstrum and we'll refer to this as *Pseudo Cepstrum*. The motivation behind this is to reduce memory usage and to decrease the execution time [32]. Examples of alternative transformations to be compared are the Hartley Transformation (HT), Discrete Cosine Transformation (DCT), Discrete Sine transformation (DST), Integer Discrete Cosine Transformation (IDCT). We focus on the DCT as an alternative transform for 2D disparity estimation, with an objective to further simplify it using a 1D projection, which could speed up computation drastically.

4.1. Alternative Pseudo Cepstrum

In order to obtain a real time IQA an efficient algorithm to compute the 2D Cepstrum is needed or a substitute transform that works faster compared to the FFT. Another variation of the traditional Cepstrum is to use the generalized Cepstrum computed using a generalized logarithmic function to control the amount of spectral smoothing and to simplify the computation of the Logarithm [33]. We study how to choose the best alterative transform in term of accuracy and robustness of disparity estimation. The HT (2) which was developed as a substitute for the Fourier Transformation when the data is real [23] was used as an alternative to the FFT in [12].

$$H[k] = \frac{1}{N}\sum_{n=0}^{N-1} h[n][\cos(\frac{2\pi nk}{N}) + \sin(\frac{2\pi nk}{N})]. \tag{2}$$

The other substitute would be the use of DCT given in (3), in place of the DFT for speech processing to reduce computational complexity substantially without degrading the information contained in the Cepstrum, given that the original signal is defined to be symmetric [34]. The DCT-Cepstrum can be computed via the relationship between DCT-II and DFT which provides a close match to the theoretical complex Cepstrum [35]. The use of DCT as an alterative can be justified based on the fact that DCT tends to project the signal in directions of maximum global variances, which produce somewhat partially uncorrelated results [36]. The use of DCT can open the door to the use of other Trigonometric transformations, which was explored by [24] and provided empirical results for using the DCT and DST for pitch period extraction.

$$H[k] = (\frac{2}{N})^{\frac{1}{2}}\sum_{n=0}^{N-1} k_n h[n]\cos(\frac{\pi n(k+\frac{1}{2})}{N}). \tag{3}$$

A faster implementation of the DCT based Pseudo Cepstrum can be achieved by using IDCT, since it only requires integer arithmetic. One shortcoming with the IDCT stems from picking one set of basis from a variety of choices, depending on the bits requirements [37]. A quick 8 or 16 IDCT size transformation can be found readily in the literature, but for a larger size basis it need to be implemented through simple computation using the C-Matrix. As the size of the IDCT block gets larger than 32, then it looses some of its advantages and the DCT performs much better [38].

In order to evaluate FFT, DCT-II, DHT and DST-II in terms of the disparity estimation using Cepstrum, we conducted simulations on 1000 $1D$ signal pairs of varying lengths and known disparities values ranging from 3 to 64. We use mean and standard deviation (STD) to evaluate the accuracy and robustness of disparity estimation, as shown in Fig. 4 and Fig. 5. During the simulation, the disparity was found by locating the global maximum in the Cepstrum domain between the sample range of 3 to 64. The reason for starting from 3 is to skip the large values that usually exist near the first two samples of the Cepstrum or Pseudo Cepstrum. The maximum disparity for any signal used was limited to half the size of the original signal.

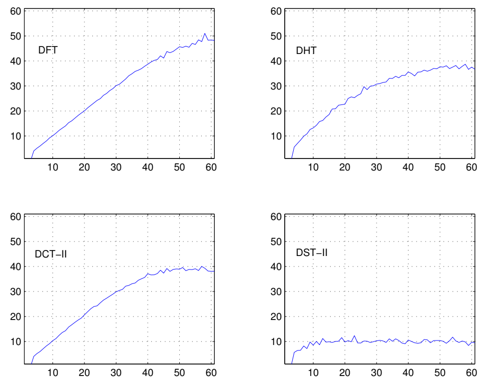

Figure 4: Simulation results of the estimated disparity values averaged over 1000 1D random signal pairs of length 128. The horizontal axis represents actual disparity and the vertical axis depicts the measured value.

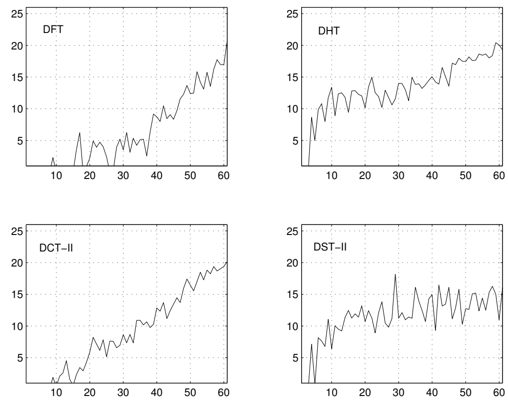

Figure 5: Simulation results of the standard deviation of estimated disparity values over 1000 1D random signal pairs of length 128. The horizontal axis represents actual disparity and the vertical axis shows the standard deviation.

Relatively speaking, for the 1D case, Fig. 4 shows that DCT-based Pseudo Cepstrum can produce similar results when compared to the FFT based Cepstrum.

4.2. 2D DCT based Pseudo Cepstrum

We want to extend the DCT-based Pesudo Cepstrum for 2D disparity estimation which includes both horizontal and vertical disparities. The simulation is based on 1000 2D RDS image pair, as shown in Table 1. FFT-based Cepstrum almost works perfect for the 2D RDS image pairs, so its results are omitted here. It is shown that DCT-based Pseudo Cepstrum can produce reliable 2-D disparity estimation when disparity amounts are not too large which is the case in our SQA application.

H/V	3	6	9	12	15	18	21	24
6	6,3	6,6	6,9	6,12	6,15	6,18	6,21	6,24
9	9,3	9,6	9,9	9,12	9,15	9,18	9,21	9,24
12	12,3	12,6	12,9	12,12	12,15	12,18	12,21	12,24
15	15,3	15,6	15,9	15,12	15,15	15,18	15,21	15,24
18	18,3	18,6	18,9	18,12	18,15	18,18	18,21	18,24.1
21	21,3	21,6	21,9	21,12	21,15	21,18	21,21	21,24
24	24,3	24,6	24,9	24,12	24,15	24,18	24,21	24,24.2
27	27,3	27,6	27,9	27,12	27,15	27,18.3	27,21.2	27,22.0

Table 1: Average (vertical,horizontal) disparity for DCT Pseudo Cepstrum applied to 1000 2D RDS stereo pair of size 64×64, with maximum disparity of 32.

Adding the two image pairs together and applying a DCT based Pseudo Cepstrum can speed up the processing time by eliminating the need for complex computation and reducing the size of the window, as shown in Fig. 3 when compared to using Cepstrum filtering on the concatenated pair. A good comparison between using a concatenated or added window for FFT based Cepstrum can be found in [39]. A further reduction in processing time can be achieved by reducing the 2D image into two 1D projection signals.

4.3. 1D Projection Pseudo Cepstrum Filtering

While the 2D Pseudo Cepstrum method can provide fast and accurate results, it still requires 2D computational complexity. One way of reducing the computational time is by projecting each 2D image into two 1D vectors along the vertical and horizontal axis, followed by Cepstrum filtering [40]. This projection method reduces the analysis window form $N \times N$ to $2 \times N$ and by further using the DCT based Pseudo Cepstrum we can speed up the processing time drastically. We have adapted this method by applying a DCT based Pseudo Cepstrum to the horizontal and vertical projection, which simplifies and speeds up the processing further. Our simulation is based on the same 1000 RDS pair used for 2D DCT-based Pseudo Cepstrum, as shown in Table 2. It is demonstrated that the 1-D projection combined with 1D DCT-based Pseudo Cepstrum can yield reasonable accuracy compared with 2D FFT-based Cepstrum and 2D DCT-based Pseudo Cepstrum.

H/V	6	9	12	15	18	21	24
6	6,6	6,9	6,12	6,15	6,18	6,21	6,24
9	9,6	9,9	9,12	9,15	9,18	9,21	9,24
12	12,6	12,9	12,12	12,15	12,18	12,21	12,24
15	15,6	15,9	15,12	15,15	15,18	15,21	15,24
18	18,6	18,9	18,12	18,15	18,18	18,21	17.9,23.9
21	21,6	21,9	21,12	21,15	21,17.9	20.9,21	20.8,23.8
24	24,6	24,9	24,12	24,15	23.9,18	23.8,20.8	23.4,23.4
27	27,6	27,9	27,12	26.9,15	26.8,18	26.1,20.7	25.2,22.6

Table 2: Average (vertical,horizontal) disparity for 1D projection Pseudo Cepstrum applied to 1000 2D RDS stereo pair of size 64×64.

5. PROPOSED STEREO QUALITY ASSESSMENT METHOD

From the simulation results, DCT based Pseudo Cepstrum produced reliable results in estimating disparity in the stereo pair. Since our hypothesis links SQA with disparity amount, we propose the use of Pseudo Cepstrum to estimate disparity in actual stereo retinal image pairs. Given the nature of retinal images with high resolution of about 6 mega pixels, with seven pairs of images for each eye, the need for fast real time algorithm becomes critical. The further simplification can be accomplished by using the 1-D projection to convert the disparity estimation from 2D to 1D.

5.1. Pseudo Cepstrum for SQA

To provide a measure of stereo quality, we start by dividing the two images (left, right) into N windows at same locations in the left and right pair. The windows which had prominent features are selected for SQA. Each window pair is then added, and both 2D and 1D DCT based Pseudo Cepstrum applied to estimate horizonal and vertical disparity. In certain windows when the features are not strong, we found that using a low pass or a gaussian filter would enhance the peak magnitude in the Cepstrum domain, and thus enhance detection of the disparity amount. Fig. 6 shows a *good* stereo retinal image pair with N analysis windows. These images were captured simultaneously using Nidek 3-DX stereo fundus camera [41]. The disparity estimation results from three different Cepstrum and Pseudo Cepstrum filtering are shown in Table 3, where we can tentatively confirm two points. One is that good stereo pairs should have much stronger horizonal disparity than vertical disparity. The other is both 1D and 2D Pseudo Cepstrums could approximate 2D FFT-based Cepstrum for disparity estimation. One interesting observation is that Cepstrum filtering of certain windows that showed strong features failed to produce an acceptable disparity estimation.

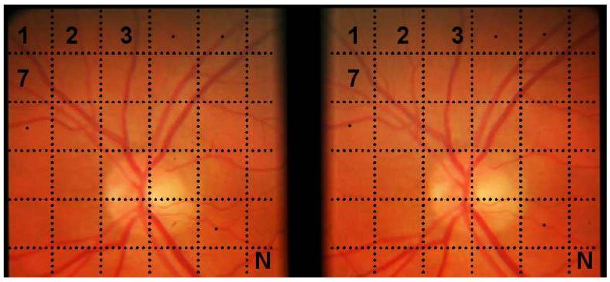

Figure 6: Left and right retinal stereo pair of size 170×140 are divided into N windows, then selected windows with prominent features are filtering using Pseudo Cepstrum to estimate disparity amount. Courtesy of Nidek, Inc. [41].

Table 3: Average disparity values over 24 blocks

	Transform used		
	FFT	2D DCT	1D DCT Projection
Vertical	4	5	5
Horizontal	13	16	15

5.2. Implementation Issues

Since the SQA tool is mainly developed for real retinal image pairs where the left and right images are captured non-simultaneously, such as the set of digitized retinal pairs from the ETDRS research group [6], we are facing some practical issues to apply Cepstrum filtering, such as:

- How to determine the number of windows N for disparity estimation as well as the appropriate window size?
- How to select proper locations of these windows to include sufficient features?
- How to determine the acceptable horizontal and vertical disparity ranges (H_{min},H_{max}, and V_{max})?

These issues can be addressed by further examination of a large set of simultaneous and non-simultaneous stereo retinal image pairs.

6. CONCLUSIONS

Certifying retinal image quality to meets ETDRS standards at the time of imaging would facilitate and speed up the imaging process. To accommodate the prevailing fundus imaging technology, an efficient SQA tool can be used to check the richness of depth information that is critical to the grading processing of DR. Although both the 1D and 2D DCT-based Pseudo Cepstrum produced promising results in term of accuracy and robustness of disparity estimation based on synthetic images and good stereo retina image pairs, its application to non-simultaneously stereo retinal images is still under investigation. A few important practical issues need to be explored in order to validate and apply the proposed SQA tool to real applications. It worth noting that the proposed research is not restricted to stereo retinal image pairs, and it can be extended to other areas and fields that rely on a single camera to capture stereo images from different views.

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