Journal of Theoretical and Applied Information Technology
31st December 2014. Vol.70 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

THE OPTIMAL QUANTIZATION MATRICES FOR JPEG IMAGE COMPRESSION FROM PSYCHOVISUAL THRESHOLD

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ABSTRACT

The JPEG image compression method has been widely implemented in digital camera devices. The quantization process plays a primary role in JPEG image compression. The quantization process is used to determine the visibility threshold of the human visual system. The quantization tables are generated from a series psychovisual experiments from several angle points of experimental views. This paper proposes psychovisual threshold through quantitative experiments for JPEG image compression. This experiment investigates the psychovisual threshold based on the contribution of DCT coefficients on each frequency order to the reconstruction error. The average reconstruction error from incrementing DCT coefficient is investigated to produce a primitive psychovisual threshold. The psychovisual threshold is designed to give an optimal balance between quality of image reconstruction and compression rates. A psychovisual threshold is obtained to generate new quantization tables for JPEG image compression. The performance of new quantization tables from the psychovisual threshold are analyzed and compared to the existing default JPEG quantization tables. The experimental results show that the new quantization tables from the psychovisual threshold produce higher quality of image reconstruction at lower average bit-length of Huffman code than default JPEG quantization tables.

Keywords: *JPEG compression, Psychovisual Error Threshold, Quantization Matrices Generation*

1. INTRODUCTION

The quantization tables are the important elements in the JPEG image compression. The quantization tables are traditionally generated from a series of psychovisual experiments to determine the visibility threshold of the human eye. A psychovisual threshold is obtained to differentiate the intensity level of the image that can be perceived visually by the human eye. The human visual perception is a complex coordination among the eye, optical nerve, visual cortex and other part of the brain [1]. The human eye does not perceive directly translation of the retina stimuli, but it involves complicated psychological inference [2].

Images are ultimately to be viewed by human beings. The proper method of quantifying visual image quality is through subjective evaluation. In practice, however, subjective evaluation is usually too inconvenient, time-consuming and expensive. Several approaches have been conducted to investigate the psychovisual threshold such as contrast sensitivity function [3], human visual weighting [4] and psychovisual model based on preserving down sampling and up sampling [5].

This research will apply the quantitative method to obtain psychovisual threshold that can predict quality image and compression rate automatically. The principle of the psychophysical adjustment method will be applied to measure the psychovisual threshold. The psychophysical adjustment method has been implemented in the psychoacoustic models to detect the audibility or hearing threshold [6]. The psychovisual threshold is measured by the impact of incrementing frequency coefficients transform one at a time to the reconstruction error. An ideal average reconstruction error from incrementing DCT coefficient on each frequency order will be a primitive psychovisual threshold. This paper proposes new quantization table generation from the psychovisual threshold in JPEG image compression.

The organization of this paper is as follows. The next section provides a brief description of the discrete Cosine transform. Section 3 presents the experimental design of the psychovisual threshold

Journal of Theoretical and Applied Information Technology
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

in JPEG image compression. The experimental results of the DCT psychovisual threshold in JPEG image compression are presented in Section 4. Lastly, section 5 provides a conclusion for the paper.

2. DISCRETE COSINE TRANSFORM

The two-dimensional DCT [7] has been widely used over the last decades in image compression. In addition, discrete Cosine transform of set $C_n(x)$ for size N=8 can be generated iteratively as follows:

$$C_0(x) = \frac{1}{\sqrt{N}},$$

$$C_1(x) = \sqrt{\frac{2}{N}} \cos\frac{(2x+1)1\pi}{2N}$$

$$C_2(x) = \sqrt{\frac{2}{N}} \cos\frac{(2x+1)2\pi}{2N}$$

$$C_3(x) = \sqrt{\frac{2}{N}} \cos\frac{(2x+1)3\pi}{2N} \quad (1)$$

For x = 0, 1, 2, …, N-1. The first four 8×8 DCT above is shown in Figure 1 for visual purposes.

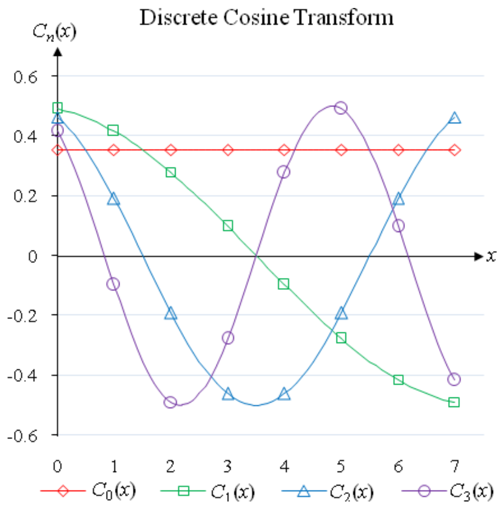

Figure 1. The first four 8×8 DCT of set $C_n(x)$ for n = 0, 1, 2, 3

The kernel for the DCT is derived from the following definition of g [8]:

$$g = \lambda(u)\cos\frac{(2x+1)u\pi}{2S}, \quad (2)$$

where $\lambda(u) = \begin{cases} \frac{1}{\sqrt{S}}, u = 0 \\ \sqrt{\frac{2}{S}}, u > 0 \end{cases}$

For x = 0, 1, 2, …, N-1 and u = 0, 1, 2, …, N-1. The definition of the two-dimensional DCT is given as follows [7]:

$$B_{pq} = \alpha_p \beta_q \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} A_{mn} \cos\frac{\pi(2m+1)p}{2M} \cos\frac{\pi(2n+1)q}{2N}, \quad (3)$$

For p = 0, 1, 2, …, M-1 and q = 0, 1, 2, …, N-1. Where A is the input image, B is the DCT coefficients and

$$\alpha_p = \begin{cases} \frac{1}{\sqrt{M}}, p = 0 \\ \sqrt{\frac{2}{M}}, p > 0 \end{cases} \quad \beta_q = \begin{cases} \frac{1}{\sqrt{N}}, q = 0 \\ \sqrt{\frac{2}{N}}, q > 0 \end{cases} \quad (4)$$

The two dimensional DCT can be computed using the one dimensional DCT horizontally and then vertically across the signals. The inverse of DCT is given as follows:

$$A_{pq} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} \alpha_p \beta_q B_{mn} \cos\frac{\pi(2m+1)p}{2M} \cos\frac{\pi(2n+1)q}{2N}, \quad (5)$$

For p = 0, 1, 2, …, M-1 and q = 0, 1, 2, …, N-1. An input image is sub-divided into 8×8 blocks of image data, each pixel block is transformed into frequency image signals by two-dimensional DCT.

3. EXPERIMENTAL DESIGN

In this experiment, the psychovisual threshold is conducted through quantitative experimental method. The 80 images (24-bit RGB with 512×512 pixels) [9] are chosen to be tested in a quantitative experiment. The images are classified into 40 real images and 40 graphical images. First, the RGB color components are converted to the YUV colour space. The RGB image should be separated into a luminance (Y) and two chrominance (U and V). The advantage of converting image into luminance chrominance color space is that the luminance and chrominance components are very much decor-related between each other [10]. Next, an image is divided into 8×8 block pixels and each block of the image data is transformed by the two-dimensional DCT.

The experiment is conducted by incrementing DCT coefficients up to a minimum and maximum of quantization value on each frequency order. JPEG quantization tables are used as a reference for a minimum and maximum of increment DCT coefficient. The effect of incrementing DCT coefficients is measured and analyzed by calculating the reconstruction error score.

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3.1. JPEG Quantization Tables

This experiment, JPEG quantization tables are used as a reference for investigating the contribution of frequency image signals. JPEG quantization step largely determines the rate distortion in a JPEG image compression [11]. The quantization table is to remove the high frequencies or discards information which is not visually significant. Therefore, JPEG quantization table is used as reference a minimum and maximum for incrementing DCT coefficients. The quantization table for luminance Q_{CL} and chrominance Q_{CR} for JPEG image compression are shown as follows:

$$Q_{CL} = \begin{bmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix} \quad (6)$$

$$Q_{CR} = \begin{bmatrix} 17 & 18 & 24 & 47 & 99 & 99 & 99 & 99 \\ 18 & 21 & 26 & 66 & 99 & 99 & 99 & 99 \\ 24 & 26 & 56 & 99 & 99 & 99 & 99 & 99 \\ 47 & 66 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \end{bmatrix} \quad (7)$$

These quantization tables were obtained from a series of psychovisual experiments which determined the visibility thresholds for the DCT basis functions in the horizontal direction and at a viewing distance equal to six times the screen width [12]. These tables have been known to offer satisfactory performance, on the average over a wide variety of applications and viewing conditions. These quantization tables have indeed been widely accepted and over years have become the default JPEG quantization tables [10].

JPEG quantization tables are to discard less visible details of the human visual systems. The quantizing the DCT coefficient process is corresponding to affect the number of bits and the quality of image reconstruction. The quantization table for chrominance components has larger values in general in comparison to the luminance component. This is done to exploit the human visual systems relative intensity to chrominance components as compared to the luminance component [12]. The quantization tables may need to be designed based on human visual sensitivity by optimizing the visual quality of the reconstructed image and given minimum bits of compressed image.

3.2. Image Reconstruction Error based on Quantization Tables from JPEG and Psychovisual Threshold

In this quantitative experiment, the effect of incrementing DCT coefficient on each frequency order is prior to generating the psychovisual threshold. The impact of incrementing DCT coefficient on each frequency order is analysed by reconstruction error and average Huffman code in image compression. The average reconstruction error of incrementing DCT coefficients on luminance (Y) and chrominance (U) for 40 real images are shown in Figure 2 and Figure 3.

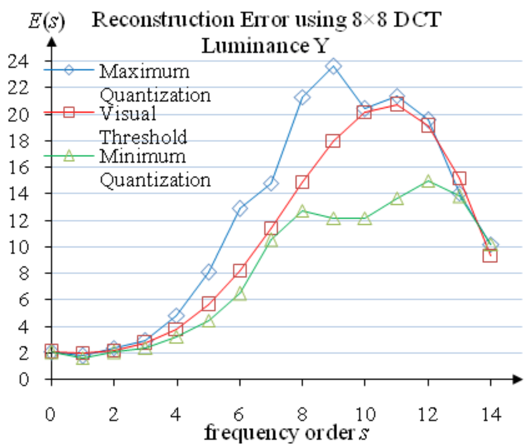

Figure 2. Average reconstruction error of incrementing DCT coefficients for 40 real color images

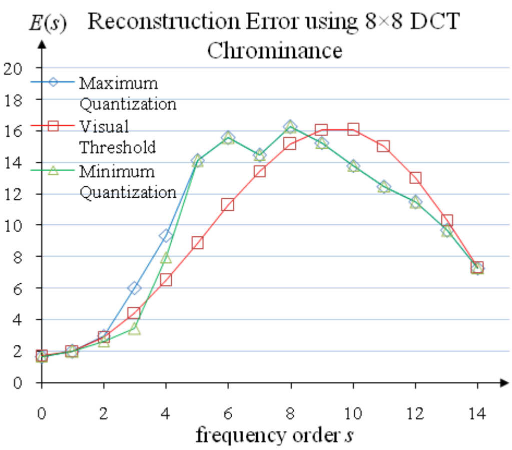

Figure 3. Average reconstruction error of incrementing DCT coefficients for 40 real color images

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Where the blue curve represents an average reconstruction error based on a maximum of the quantization value and the green curve represents the average reconstruction error based on a minimum of quantization value from order zero to fourteen. In order to measure a psychovisual threshold, the average reconstruction error is set as a smooth transition of an ideal curve of average reconstruction error. An ideal psychovisual threshold is designed to give an optimal balance between reconstruction error and compression rate. The psychovisual threshold for luminance and chrominance are represented by a red curve.

Following the principles of the psychoacoustic model, it can be stressed that human receptor is more sensitive to changes in (low order frequency) sound such as a whisper. This psychovisual threshold takes into consideration on the human eyes which is more sensitive to the low order of frequency signals than to constant image patterns. The psychovisual threshold is used to prescribe the new quantization values.

3.3. The New Quantization Table Design

According to the psychovisual threshold, the quantization values are generated for each frequency order. The smooth curve of the average reconstruction error is interpolated by polynomial functions. Referring to Figure 2 and Figure 3, the authors propose the DCT psychovisual threshold for luminance f_{VL} and chrominance f_{VR} are defined as follows:

$$f_{VL}(x) = 0.00005715x^6 - 0.002x^5 + 0.0202x^4 - 0.0561x^3 + 0.1683x^2 - 0.1743x + 2 \quad (8)$$

$$f_{VR}(x) = 0.0002785x^5 - 0.0082x^4 + 0.0471x^3 + 0.2082x^2 + 0.0588x + 1.7 \quad (9)$$

For $x = 0, 1, 2, ..., 14$.

According to (8) and (9), these functions are used to generate the new quantization matrices for luminance and chrominance as follows:

$$Q_{VL} = \begin{bmatrix} 16 & 14 & 13 & 15 & 19 & 28 & 37 & 55 \\ 14 & 13 & 15 & 19 & 28 & 37 & 55 & 64 \\ 13 & 15 & 19 & 28 & 37 & 55 & 64 & 83 \\ 15 & 19 & 28 & 37 & 55 & 64 & 83 & 103 \\ 19 & 28 & 37 & 55 & 64 & 83 & 103 & 117 \\ 28 & 37 & 55 & 64 & 83 & 103 & 117 & 117 \\ 37 & 55 & 64 & 83 & 103 & 117 & 117 & 111 \\ 55 & 64 & 83 & 103 & 117 & 117 & 111 & 90 \end{bmatrix} \quad (10)$$

$$Q_{VR} = \begin{bmatrix} 18 & 18 & 23 & 34 & 45 & 61 & 71 & 92 \\ 18 & 23 & 34 & 45 & 61 & 71 & 92 & 92 \\ 23 & 34 & 45 & 61 & 71 & 92 & 92 & 104 \\ 34 & 45 & 61 & 71 & 92 & 92 & 104 & 115 \\ 45 & 61 & 71 & 92 & 92 & 104 & 115 & 119 \\ 61 & 71 & 92 & 92 & 104 & 115 & 119 & 112 \\ 71 & 92 & 92 & 104 & 115 & 119 & 112 & 106 \\ 92 & 92 & 104 & 115 & 119 & 112 & 106 & 100 \end{bmatrix} \quad (11)$$

The visualization of new quantization tables from the psychovisual threshold for luminance and chrominance are shown in Figure 4 and Figure 5.

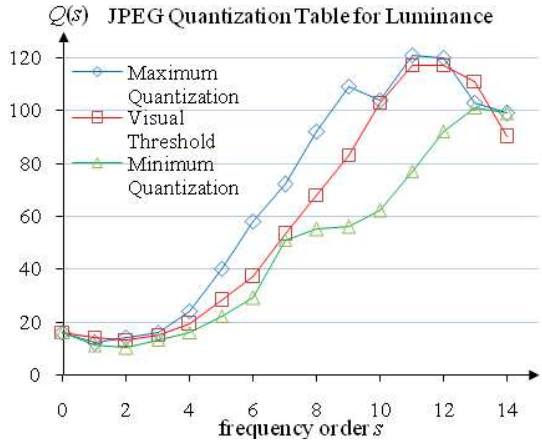

Figure 4. The visualization of the quantization table from the psychovisual threshold for luminance

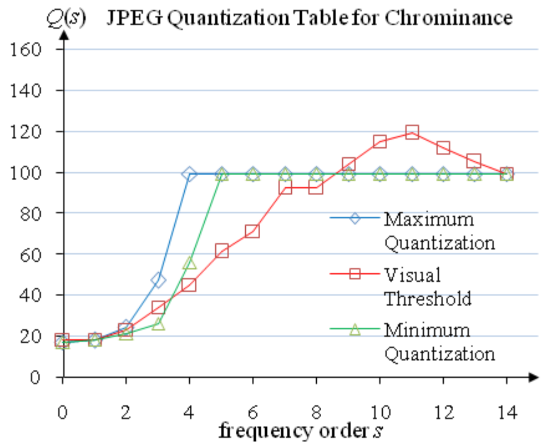

Figure 5. The visualization of the quantization table from the psychovisual threshold for chrominance.

The design of over large quantization value at low frequency signals causes blocking image, while the over large quantization value at higher frequencies lead to random noise becoming visible [13]. The psychovisual threshold provides an optimal balance between quality of image reconstruction and compression rate.

Journal of Theoretical and Applied Information Technology
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

4. EXPERIMENTAL RESULTS

In order to evaluate the effectiveness of the psychovisual threshold, the new quantization tables from the psychovisual threshold are applied in JPEG image compression as illustrated in Figure 6. The JPEG image compression scheme is adopted to measure the performance of the psychovisual threshold in terms of image quality and average bit length of Huffman code of the compressed image.

Following JPEG image compression techniques, each component array of the image input is divided into 8×8 block image pixels. Each block is transformed by two-dimensional DCT in order to reconfigure the information in the image signals. For each component, the transformed coefficients are quantized separately. The quantization step is the process which removes the high frequencies presented in the original image. This is done by dividing each element of the frequency coefficients by responding to elements in 8×8 quantization tables and rounding the results. Thus, the DC coefficients are separated with the AC coefficients. Next, run length encoding is used to reduce the size of repeating coefficients in the sequence of a set of AC coefficients. Run length coding is a simple technique to obtain coefficients when there is a long run of the same value. The coefficients can be represented compactly by simply indicating the value and the length of its run when it appears. The output of run length coding represents a value of the pixel as symbols and the length of occurrence of the symbols. The symbols and variable length of occurrence are used in Huffman coding to retrieve code words and their length of code words. An average bit-length of DC coefficients and AC coefficients of Huffman code shall be computed.

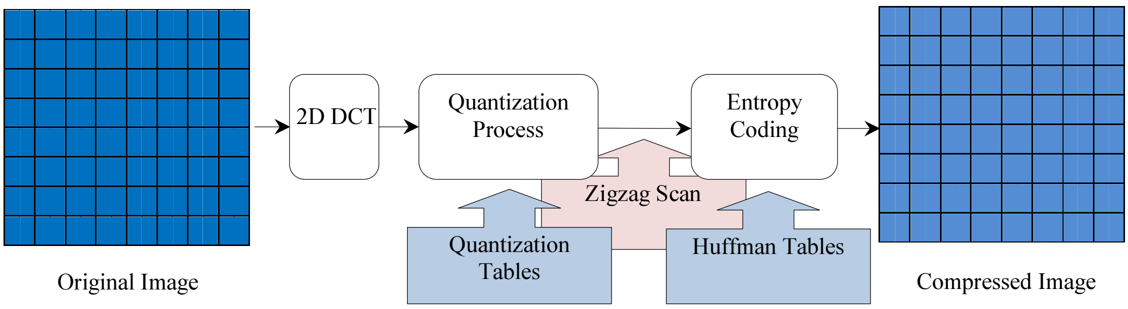

Figure 6. JPEG image compression consists of two-dimensional DCT

4.1. Huffman Coding

Huffman coding is a coding technique to produce the shortest possible average code length of the source symbol set and the probability of occurrence of the symbols [14]. Using these probability values, a set of Huffman code of the symbols can be generated by Huffman Tree. Next, the average bit length score is calculated to find the average bit length of DC and AC coefficients. The Huffman codes are stored in the Huffman Table. For an image with three components, the encoder can store four sets of Huffman tables (AC tables for luminance and chrominance) and (DC tables for luminance and chrominance). Huffman tables are stored as header information in the compressed image file in order to uniquely decode the coefficients during the decompression process [14]. The average bit length of Huffman code based on the default JPEG quantization tables and the new quantization tables from DCT psychovisual threshold for 40 real images and 40 graphical images are shown in Table 1 and Table 2.

Table 1. Average bit length of Huffman code on image compression for 40 real images

Image Measurement	JPEG quantization tables	Quantization tables from psychovisual threshold
DC Luminance (Y)	5.7468	5.7468
DC Chrominance (U)	2.7941	2.7174
AC Luminance (Y)	2.8680	2.7966
AC Chrominance (U)	2.0950	2.0718

Table 2. Average bit length of Huffman code on image compression for 40 graphical images

Image Measurement	JPEG quantization tables	Quantization tables from psychovisual threshold
DC Luminance (Y)	5.5236	5.5236
DC Chrominance (U)	4.2475	4.1230
AC Luminance (Y)	2.9992	2.9637
AC Chrominance (U)	2.4784	2.3349

4.2. Quality Measurement

In order to validate the effectiveness of the psychovisual threshold, the image reconstruction error is calculated by obtaining the differences between image reconstruction $g(i, j, k)$ and original

Journal of Theoretical and Applied Information Technology
31st December 2014. Vol.70 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

image $f(i, j, k)$. The image reconstruction error can be defined as follows:

$$E(s) = \frac{1}{3MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \sum_{k=0}^{2} \left| g(i,j,k) - f(i,j,k) \right| \quad (12)$$

where the original image size is $M \times N$ and the third index refers to the value of the RGB colour. Another convenient measurement is the Means Squared Error (MSE), it calculates the average of the square of the error. The MSE is defined as follows [15]:

$$MSE = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \sum_{k=0}^{2} \left\| g(i,j,k) - f(i,j,k) \right\|^2 \quad (13)$$

The next measurement is Peak Signal to Noise Ratio (PSNR). The PSNR is defined as follows [16]:

$$PSNR = 10 \log_{10} \left(\frac{255^2}{MSE} \right) \quad (14)$$

Another measurement quality image is Structural Similarity index (SSIM), which is a method to measure the similarity between original image and compressed image. The SSIM is defined as follows:

$$SSIM(x,y) = [l(x,y)]^{\alpha} . [c(x,y)]^{\beta} . [s(x,y)]^{\gamma} \quad (15)$$

where $\alpha > 0$, $\beta > 0$, $\gamma > 0$, are parameters to adjust the relative importance of the three components. The detail description is given in [17]. The quality of image reconstruction from the default JPEG quantization tables and DCT psychovisual threshold for 40 real images and 40 graphical images are listed in Table 3 and Table 4.

Table 3. The quality of image reconstruction for 40 real images

Image Measurement	JPEG quantization tables	Quantization tables from psychovisual threshold
Full Error	5.5348	5.4987
MSE	70.9635	69.5199
PSNR	31.1903	31.2516
SSIM	0.9557	0.9548

Table 4. The quality of image reconstruction for 40 graphical images

Image Measurement	JPEG quantization tables	Quantization tables from psychovisual threshold
Full Error	6.1479	5.8087
MSE	113.8332	100.0520
PSNR	29.7903	30.2278
SSIM	0.9541	0.9615

The experimental results show the new quantization tables from the psychovisual threshold performs better on the quality of image reconstruction at lower average bit length of Huffman code than standard JPEG image compression. In this experiment, the right eye of the baboon image is evaluated as shown in Figure 7. In order to observe the effectiveness new quantization tables from the psychovisual threshold, the image output is zoomed in to 400% as depicted on the right of Figure 8. The experimental result from the JPEG image compression is shown on the left of Figure 8.

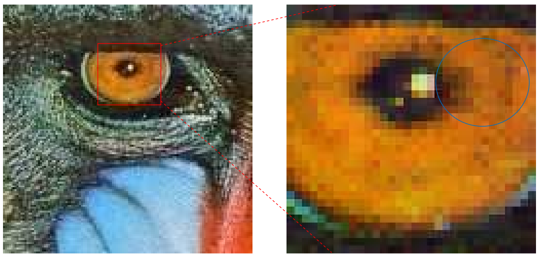

Figure 7. Original color image (left) and zoomed in to 400% (right).

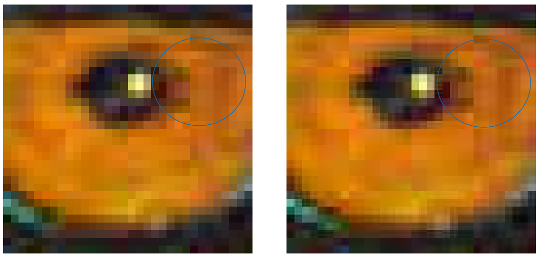

Figure 8. The comparison between JPEG quantization tables (left) and quantization tables from the psychovisual threshold (right) zoomed in to 400%.

Referring to the left pictures of Figure 8, the standard JPEG based line coding produces artifact image and gives a blurred image output when the image data was zoomed in to 400%. The new quantization tables from the psychovisual threshold for JPEG image compression produces slightly better visual quality of the image output than standard JPEG coding as depicted in the blue circle on the right of Figure 8. The new quantization tables from the psychovisual threshold produce a lower average bit length of Huffman code as listed in Table 1 and Table 2. In addition, the psychovisual threshold also produces better quality of image reconstruction in comparison to the default JPEG quantization tables as presented in Table 3 and Table 4. The quantization tables are to discard less visible details of human visual systems and to achieve efficiency high compression. The quantized DCT coefficients affect the number of bits and the quality of image reconstruction.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

5. CONCLUSSION

The quantization tables are the crucial element in JPEG image compression performance. The quantization process has a primary role in reducing the redundancy visual image information in image compression. This paper presents a novel DCT psychovisual threshold to generate quantization tables. The DCT psychovisual threshold provides an ideal threshold of the detail limited sensitivity of DCT basis function in image compression. This threshold provides an optimal balance between the output image quality and compression rate. The experimental results show the new quantization tables from the psychovisual threshold provide better quality of image reconstruction at lower average bit length of Huffman code than standard JPEG image compression.

6. ACKNOWLEDGMENT

The authors would like to express a very special thanks to Universitas Dian Nuswantoro, Indonesia for providing financial support for this research project.

REFRENCES:

[1] R. Strenberg. Cognitive Psychology. Third Edition, Thomson Wadsworth, 2003.

[2] G. Zhai, X. Wu, X. Yang, W. Lin and W. Zhang, "A Psychovisual Quality Metric in Free-Energy Principle," *IEEE Transactions on Image Processing*, Vol. 21, No. 1, Jan. 2012, pp. 041-052.

[3] H.A. Peterson, A.J. Ahumada and A.B. Watson, "An Improve Detection Model for DCT Coefficient Quantization," *Proceeding of SPIE* Vol. 1913/91, 1995.

[4] K.N. Ngan, K.S. Leong and H. Singh, "Adaptive Cosine Transform Coding of Images in Perceptual Domain," *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol. 37, No. 11, Nov. 1989, pp. 1743-1750.

[5] G. Zhai, X. Wu and Y. Niu, "A Psychovisually Tuned Image Codec," *International Workshop on Multimedia Signal Processing*, Oct. 2011, pp. 001-006.

[6] H. Fastl and E. Zwicker, 2007. "Psychoacoustics Facts and Models," Springer Series in Information Sciences, pp. 17.

[7] N. Ahmed, T. Natrajan and K.R. Rao, "Discrete Cosine Transform," *IEEE Transactions on Computers*, Vol. 23, No. 1, Jan. 1979, pp. 90-93.

[8] R. Mukundan and O. Hunt, "A Comparison of Discrete Orthogonal Basis Functions for Image Compression," *Proceeding Conference on Image and Vision Computing* (IVCNZ 2004), pp. 053-058.

[9] R. Rodriguez-Sanchez, J. Martinez-Baena, A. Garrido, J.A. Garcia, J. Fdez-Valdivia, M.C. Aranda, "Computer Vision Group," University of Granada. [Online]. 2002. Available: http://decsai.ugr.es/cvg/dbimagenes/c512.php

[10] W.B. Pennebaker and J.L. Mitchel, "JPEG Still Image Data Compression Standard," Springer, New York, USA, 1992.

[11] E.H. Yang and L. Wang, "Joint Optimization of Run-Length Coding, Huffman Coding, and Quantization Table with Complete Baseline JPEG Decoder Compatibility," *IEEE Transactions on Image Processing*, Vol. 18, No. 1, Jan. 2009, pp. 063-074.

[12] A.C. Bovik, "The Essential Guide to Image Processing," Elsevier Press, 2009, pp. 429-432.

[13] D.L. McLaren and D.T. Nguyen, "Removal of Subjective Redundancy from DCT-Coded Images," *IEE Proceedings Communications, Speech and Vision*, Vol. 138, No. 5, Oct. 1991, pp. 345-350.

[14] D.A. Huffman, "A Method for the Construction of Minimum-Redundancy Codes," *Proceedings of the IRE*, Vol. 40, No. 9, Sep. 1952, pp. 1098-1101.

[15] R. Sakuldee and S. Udomhunsakul, "Objective Performance of Compressed Image Quality Assessments," *Proceeding of World Academy of Science, Engineering and Technology*, Vol. 26, Dec. 2007, pp. 434-443.

[16] M. Mrak, S. Grgic and M. Grgic, "Picture Quality Measures in Image Compression Systems," *IEEE Region 8 Computer as a Tool* (EUROCON 2003), Vol. 1, 2003, pp. 233-236.

[17] Z. Wang, A.C. Bovik, H.R. Sheikh and E.P. Simoncelli, "Image Quality Assessment: From Error Visibility to Structural Similarity," *IEEE Transactions on Image Processing*, Vol. 13, No. 4, Apr. 2004, pp. 600-612