VLLCVD Subjective Image Fidelity Criteria and Its Applications

Day-Fann Shen, Jen-Hsing Sung, W.C. Fan, M.Z. Lin, J.G. Fun, Z.H. Shen, F.K. Tsai and Y.Z. Shin
Signal Compression and Multimedia Communication Laboratory
Department of Electrical Engineering
Yunlin University of Science and Technology, Douleo, Yunlin, Taiwan

Abstract

Human eyes is often the final receiver of digital images, human visual system plays an important role in digital image processing. Three of the issues in image processing related to human visual perception are (1) Criteria for evaluation of image fidelity, (2) Definition of *visually lossless* image in image coding or *invisible* image in watermarking and (3) Criteria for evaluation of human visual models. Many criteria, such as SNR, PSNR, MSE etc., are available for the first issue, but these criteria have well-known drawbacks in reflecting the true perceived image quality. Even worse, criteria for the second and third problems are seldom heard. In this paper, we resolve the three problems simultaneously, under a unified and accurate subjective VLLCVD (Visually LossLess Critical Viewing Distance) criteria.

1. Introduction

Since human visual system (HVS) is the final receiver of image and video, it is very important to incorporate human visual properties (HVP) in various image-processing tasks, such as image coding, image segmentation and invisible image watermarking. In image coding application, the perceptual image quality can be optimized by effective bits allocation according to HVP that same amount of bits can achieve better perceptual image quality.[1-10] Image segmentation is a process required by MPEG-4 as well as image analysis and computer vision tasks. The HVP based pixel/region merge criteria in image segmentation is proven to be a simple and effective alternative to the complicated statistically based merge criteria in image segmentation.[11] In invisible image watermarking, sufficient amount of watermark signals can be added to an image without being noticed by human perception, while increasing the robustness to attacks from pirates.[12~16] All the above applications require effective incorporation of visual properties.

HVS and consequently HVPs are quite complicated,[19] a complete description of the HVS and HVPs is not practical and unnecessary. Instead, an efficient and effective representation of HVPs in terms of a human visual model (HVM) is normally sufficient for a particular image-processing task. Among the HVPs, Just Noticeable Difference (JND) property is the most frequently used. JND property states the fact that HVS's sensitivity to visual stimuli is no unlimited, it cannot detect the difference between two visual components, if the difference is smaller than a certain threshold. Further, HVS's sensitivity is not linear to all visual stimuli, that is, visual contents of different luminance and frequencies are weighted differently by HVS. In addition, other factors including ambient lighting condition, quality of the image display monitor, viewing distance and personal eye sight may influence HVS's sensitivity to image distortions and therefore the perceived image fidelity or quality.

Many JND based HVMs have been proposed,[1-16] these HVMs were derived by researchers using different approaches and under different viewing conditions. For example, Watson et al. proposed HVMs in the form of DCT quantization matrices for individual images,[9b] visibility of DCT basis function[9c] and the visibility of wavelet quantization noises,[9a] which were derived from DWT (Discrete Wavelet Transform) basis function stimuli and DWT uniform quantization noise stimuli. While Chou et al.[8] derived a JND/MND profile in spatial domain for an image by considering the local property for each pixel, including the background luminance as well as the texture masking effects. The JND/NMD profile is then transformed into (DCT or Wavelet) subbands and assigned different weights for each subband according to HVS's sensitivity to each subband.[8] Shen et al.[6] derived a JND model based on measurements of JND threshold on square waves of different frequencies and directions;[6,7] the result is a set of JND thresholds for each wavelet subband.

Three of the issues in image processing related to human visual perception are (1) Criteria for the evaluation of image fidelity, i.e. given two decoded lossy images, how do we judge which image has better image fidelity? (2) Definition of visually lossless image, i.e. given an lossy image claimed to be "visually lossless", "near-lossless" or "invisible watermarked", how do we verify whether the claim is true or not? and (3) Criteria for evaluation of human visual models, i.e. given two HVMs,[1-16] which HVM provide better performance? In fact, we think that these three issues are closely related and a solid solution to the first issues is the key to the other two.

For the first issue, many well-known criteria such as SNR, PSNR, MSE etc. are common used, but these criteria have drawbacks in reflecting the true perceived image quality. Currently, there are three categories of criterion for assessing the fidelity of a lossy image, they are (1) Objective (computable) fidelity criterion (OFC) (2) Subjective (human tester) fidelity criterion (SFC) (3) Visually weighted Objective fidelity criterion (VWOFC).[17,18] Given a lossy image and its original, an OFC estimates the fidelity by computing numerical differences between the image pair. Examples of OFC are SNR (Signal to Noise Ratio), PSNR (Peak Signal to Noise Ratio), MSE (Mean Square Error) or RMSE (Root Mean Square Root), the result is a real number indicating the degree of fidelity between the lossy image and the original. OFC is easy to compute and is a widely adopted image fidelity criterion, however, it is well known that OFC does not always consistent with human perceptions, that is, an image with better OFC is not necessary better in perception.

To overcome this shortcoming, the VWOFC assigns different weights to errors in different image components according to a human visual model. It is expected that the results from VWOFC are more consistent with human perception while without involving the time consuming SFC which requires efforts from a group of testers. It is noted that VWOFC is visual model dependent, it would be inadequate (unfair) in assessing human visual models.

Nevertheless, human eyes are the final receivers of an image and are naturally the best judges of the image fidelity. For serious image fidelity evaluations, in spite of requiring human efforts and time consuming, SFC is often adopted instead of OFC or VWOFC. A SFC calls for a group of human testers (or observers, umpires) who are responsible to rate the fidelity at their subjective judgments (just like the 10 umpires in a international ice-skiing competition). For example rating 1 to 5 may corresponds to 1- Absolutely unable to distinguish, 2-Almost unable to distinguish, 3- difficult to distinguish, 4- Easy to distinguish and 5- Very easy to distinguish. The average rating from all testers then indicates the degree of fidelity. The above FSC has at least two drawbacks: it requires efforts from a group of human testers and it is time consuming; Secondly, SFC by rating is vague and not precise. Average rating from a SFC reflects the fidelity of a decoded image perceived by average human beings.

Currently, the solutions for the 2nd (verifying *visually lossless* or *invisibility* of images) and 3rd (evaluation of HVMs) issues are seldom reported. With no clear definition of "*visually lossless*" or "*invisibility*", it is difficult to verify the claim of a lossy image to be visually lossless. For example, the emerging JPEG2000 image-coding standard includes the options for visually lossless images. Many researchers claim that their encoded/decoded images are visually lossless, yet if we examine those images closely under a strict viewing condition, such as in a dark room at night at very short distance, differences between the original and the decoded images can be detected. For this reason, serious image users, like physician and radiologist, are reluctant to use so call *visually lossless* images. Similarly, many VHM[1-16] are proposed by researchers, but few criteria are available to help the selection and comparison of human visual models.

A solid solution to the first issue is the key to the other two issues. However, from the above discussion, none of the current criterion is solid enough. In this paper, we propose a SFC based criterion called VLLCVD (Visually LossLess Critical Viewing Distance) for resolving the above three visual perception related issues simultaneously. The VLLCVD criterion is more precise and is based on the SPS (Same Position Swapping) technique and the VLLCVD measurements. The SPS technique utilizes the fact that HVS is sensitive to differences between two swapping images; while the VLLCVD yields a score in distance (in cm or inch), which is precise and powerful. Criterions for 2nd and 3rd issues are then proposed based on the VLLCVD. We also propose a computable C_VLLCVD for the estimation of VLLCVD without the time consuming human testing.

This paper is organized as followings. In the second section, we define the observation conditions for the SFC measurements; In the third section, the SPS technique and VLLCVD measurement are illustrated. In the fourth section, the two subjective fidelity scores are defined based on the VLLCVD measurements. In the fifth section, we demonstrate the application of the proposed SFC in evaluation and comparison of two visual models in the context of image coding. Conclusion is made in Section 6.

2. Conditions for Experiments

Many parameters (factors) may affect the observations and consequently the result of the proposed VLLCVD. These parameters are adjusted to minimize the uncertainties as well as maximize each tester's HVS sensitivity.

1. The surrounding lighting condition: All observations are conducted in a dark room at night with no other light sources except the PC monitor in use. This guarantees the smallest variation in surrounding lighting condition as well as increases the sensitivity of human visual perception.
2. Monitor: SONY 20 inches CRT Colour monitor for workstation (Model-GDM) is used with Contrast and Brightness knobs adjusted to yield the sharpest and most clear images to each subject tester.
3. N Testers: 6 volunteers from the image processing class, ages range from 20 to 24 and eyesight from 0.8 to 1.2. Their personal data is listed in Table I. For unbiased judgment, testers are not told anything about the images under test..
4. Observation method: SPS and VLLCVD to be described in the next section.

Among the above conditions, two of them may cause higher uncertainty in the measurements:

1. The characteristics of monitor in use and the settings of its contrast and brightness knobs.
2. The physical and mind conditions of the testers**.**

3. The VLLCVD Subjective Measurements

3.1 The SPS Technique

Instead of placing two images side by side, the SPS (Same Position Swapping) technique places the decoded image on top of its original i.e. both are displayed in the same position on the center of the monitor. The occluded image in the bottom can be swapped to the top by clicking the mouse, the human perception is more sensitive to the differences during swapping. For better focus of the testers' attention, both the lossy and the original images are divided into 128*128 sub-blocks using thin lines (one pixel in width, 180 gray levels).

3.2 The VLLCVD Procedure

Step1: Set up the observation environment as described in section 2. The lossy image $\mathbf{f}'$ (decoded or watermarked image) and its original $\mathbf{f}$ are displayed on the screen as required by the SPS technique.

Step 2: Begin at the Initial Viewing Distance (IVD) (from the center of the screen to the center of the tester's eye) of 60 cm, a tester $\boldsymbol{t}$ pays full attention on examining a sub-block at a time using the SPS technique for each sub-block. If any noticeable difference at any sub-block is found, tester $\boldsymbol{t}$ reports the areas where noticeable differences occurs and go to Step 3. Otherwise, if no difference is found, then go to Step 4.

Step 3: Tester $\boldsymbol{t}$ gradually increases the Viewing Distance (VD) (away from the screen) until no noticeable difference are found for all sub-blocks. Go to Step 5.

Step 4: Tester $\boldsymbol{t}$ gradually decreases the Viewing Distance (VD) (close to the screen) until no noticeable difference are found in all sub-blocks, and then go to Step 5. If for any distance includes viewing distance of zero (the tester's forehead and nose touch the screen), no difference can be found, then go to Step 6.

Step 5: At this point, lossy image $\mathbf{f}'$ is regarded as Visually LossLess (VLL) for tester *t*. Record this Critical Viewing Distance in *cm* as the VLLCVD for lossy image $\mathbf{f}'$ and tester $\boldsymbol{t}$ or more precisely $cd_{VLL}(f, f', t)$.

Since differences between lossy image $\boldsymbol{f}'$ and its original is still noticeable at viewing distances smaller than $cd_{VLL}(f, f', t)$, lossy image $\boldsymbol{f}'$ is not Absolutely Visually LossLess (AVLL) for tester $\boldsymbol{t}$, we record $AVLL(f, f', t)=0$.

Step 6: The differences between lossy image $\boldsymbol{f}'$ its original is not noticeable at any viewing distance for tester $\boldsymbol{t}$, lossy image $\boldsymbol{f}'$ is regarded as ***AVLL*** (Absolutely Visually LossLess) for tester $\boldsymbol{t}$ and is denoted as $AVLL(f, f', t)=1$ which implies $cd_{VLL}(f, f', t)=0$.

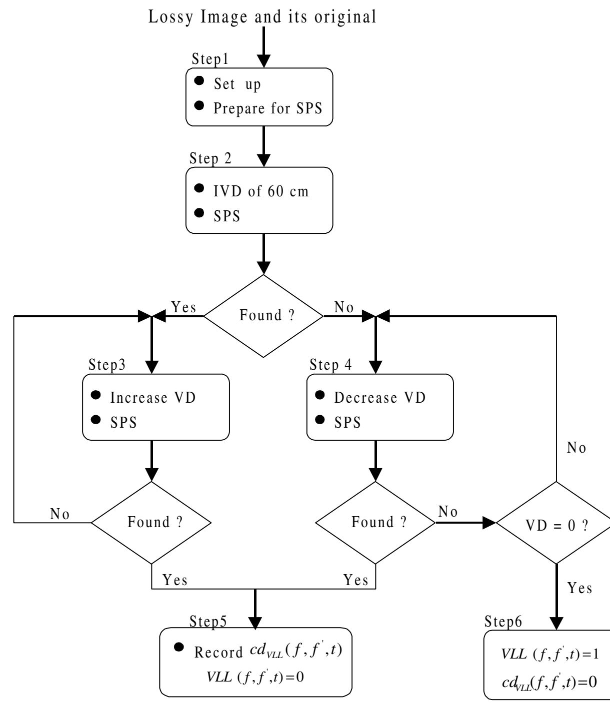

Figure 1: The VLLCVD Procedure

Figure 1 shows the flowchart of the proposed VLLCVD subjective Fidelity Criterion. It is noted that for any VD smaller than $cd_{VLL}(f,f',t)$, lossy image f' is always VLL to tester *t*.

4. The VLLCVD Subjective Fidelity Criteria- Resolving the 1st and 2nd Problems

For a lossy image $\boldsymbol{f}'$, we define two subjective fidelity criterions $S_{cd}(f, f')$ and $S_{av}(f, f')$ based on $cd_{VLL}(f, f', t)$ and $AVLL(f, f', t)$ recorded by all testers.

VLLCVD Fidelity Criterion (Resolving Problem #1):

1. The subjective fidelity of a lossy image $\boldsymbol{f}'$ to tester $\boldsymbol{t}$ is measured by the VLLCVD $cd_{VLL}(f, f', t)$.
2. It is also noted that the smaller distance $cd_{VLL}(f, f', t)$, the better fidelity of the lossy image. $\boldsymbol{f}$ to tester $\boldsymbol{t}$**.** The subjective fidelity of a lossy image $\boldsymbol{f}'$ (to common viewers) is estimated by $S_{cd}(f, f')$, the average VLLCVD.

$$S_{cd}(f, f') = \frac{\sum_{\langle testers \rangle} cd_{VLL}(f, f', t)}{N_{cd}}, \quad S_{cd} > 0$$

N_{cd} is the number of testers who can notice differences between f' and its original. (i.e. $cd_{VLL}(f, f', t) \neq 0$). The larger N_{cd}, the better the estimation.

Defining Visually LossLess (*VLL*) of a lossy image (Resolving Problem #2)

3. Lossy image f' is ***VLL*** to tester ***t*** for viewing distance VD > $cd_{VLL}(f, f', t)$. By this definition, any image can be ***VLL*** to tester ***t*** if VD is far enough.
4. Lossy image f' is ***VLL*** (to common viewers) for viewing distance VD > $S_{cd}(f, f')$. By this definition, any image can be ***VLL*** if VD is far enough.

Defining Absolutely Visually LossLess (*AVLL*) of a lossy image (Resolving Problem #2)

5. Lossy image f' is ***AVLL*** to tester ***t*** if $AVLL(f, f', t) = 1$ (i.e. $cd_{VLL}(f, f', t) = 0$).
Tester ***t*** cannot detect the difference at any distance under the test environment.

6. Lossy image f' is ***AVLL*** (to common viewers) with *degree* $S_{av}(f, f')$. Where

$$S_{av}(f,f') = \frac{\sum_{(testers)} AVLL(f,f',t)}{N_T}, \quad S_{av} \in \{\frac{0}{N_T}, \frac{1}{N_T}, \frac{2}{N_T}, ..., \frac{N_T}{N_T}\}$$

N_T is the total number of testers involved. $S_{av}(f, f') = 0$ indicates that no single tester regards image f' as ***AVLL***, while $S_{av}(f, f') = 1$ indicates that all testers regard image f' as ***AVLL***.

The above subjective criteria are more precise in reflecting the true image fidelity perceived by human eyes as well as defining the visually lossless of a lossy image or invisibility of a watermarked image. By these precise criteria, we are able to evaluate and compare visual models.

5. Comparison of Human Visual Models

Visual models play important roles in image coding, digital image watermarking[1-16] as well as other image processing tasks. *The question* is given two visual models, which one is better? Two key ideas in our answer to this question are (1) The proposed VLLCVD subjective criteria is adopted as the main image fidelity measure, for they are more precise in reflecting the human perception. In addition, two other fidelity criteria JND_PSNR and JND_MSE (to be defined in this section) are also used in the experiment (2) choosing the visual model, which yields better coding performance (image fidelity versus bit per pixel (bpp)) for a range of bit rates and for various test images. Of course, same coding algorithm should be employed.

As an example, we evaluate and compare two wavelet-based visual models: SY model[6] and Watson model.[9] Both are in the form of SQT (Subband Quantization Table) as shown in Table 1 and 2. Although these two visual models are derived using different approaches under different viewing conditions, fair comparisons still can be achieved by evaluating various image fidelities vs. bit rates.

Table 1. Basic SQT derived from SY JND model with display resolution=26.256 pixels/degree at 60 cm viewing distance

View distance = 60 cm

Subband	Step size	Subband	Step size
HH1	52.59	LH3	6.00
HL1	14.11	HH4	6.00
LH1	15.27	HL4	6.00
HH2	11.93	LH4	6.00
HL2	6.35	HH5	6.00
LH2	6.34	HL5	6.00
HH3	6.94	LH5	6.00
HL3	6.00	LL5	6.00

Table 2. Basic SQT derived from Watson's JND model with display resolution of 32 pixels/degree at 70 cm viewing distance

View distance = 70 cm

Subband	Step size	Subband	Step size
HH1	58.76	LH3	12.71
HL1	23.03	HH4	17.86
LH1	23.03	HL4	14.16
HH2	28.41	LH4	14.16
HL2	14.68	LL4	14.50
LH2	14.69	HH5	*
HH3	19.54	HL5	*
HL3	12.71	LH5	*

SPIHT with JND_SQ shown in Fig. 2 is adopted as the image coding algorithm, where $\{S_{sb}\}$ is the adjusted SQT obtained by multiplying the basic SQT (in Table 1 or 2) with a Compression Control Factor (CCF) ϕ. Images with various bit rates and fidelities can be obtained by adjusting ϕ.

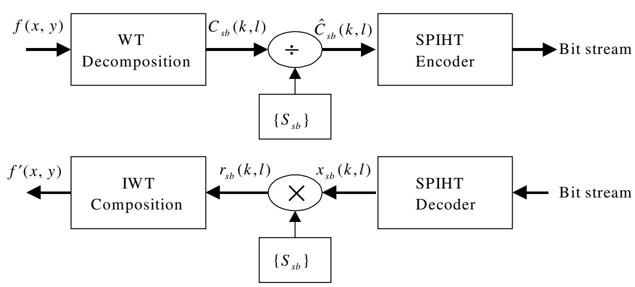

Figure 2. Block Diagram of JND_SPIHT

The JND based scalar quantization (JND_SQ) and reconstruction scheme:

$$\begin{cases} \hat{C}_{sb}(k,l) = round\left[\frac{C_{sb}(k,l)}{S_{sb}}\right] \\ C_{sb}(k,l) = x_{sb}(k,l) \cdot S_{sb}, \quad S_{sb} = SQT_{sb} \bullet \phi \end{cases}$$

In addition to the well-known PSNR, we also define JND_PSNR and JND_MSE – the VWOFC as follows: Definitions:

$$JND\_PSNR = 10 \log \frac{255^2}{JND\_MSE}$$

$$JND\_MSE = \frac{\sum_{sb=1}^{n} JND\_Err_{sb}}{N}$$

Where *sb* is the subband, *n* is the total number of subbands and N is the number of total pixels. And

$$JND\_Err_{sb} = \sum_k \sum_l \left[\Psi(\left|c_{sb}(k,l) - r_{sb}(k,l)\right| - \phi_{avll} \cdot S_{sb} / 2) \right]^2 / w_{sb}{}^2$$

$$x = \left|c_{sb}(k,l) - r_{sb}(k,l)\right| - \phi_{avll} \cdot S_{sb} / 2, \quad \begin{cases} \Psi(x) = x, x > 0, \\ \Psi(x) = 0, x \le 0 \end{cases}$$

$$w_{sb} = \frac{S_{sb}}{6.0}.$$

Where w_{sb} is the visual weight for subband *sb,* the weight for the lowest subband is normalized to w_{sb} = 1.0.

Definition: Compression Control Factor of Absolute

Visually LossLess, denoted as ϕ_{avll}, is the value of ϕ such that all test images are *AVLL* to all testers or ($S_{av}(f, f')$ =1 for all test images).

In the experiments in our laboratory (6 testers, with three test images (Lena256x256, F-16256x256 and salesman256x256), the value of ϕ_{avll} is found to be 0.4 for SY model and 0.15 for Watson's model (gray level or Y component). It is understood that the value of ϕ_{avll} depends on testers' eye sights and the test images, however, for a fair comparison purpose, Adopting ϕ_{avll} =0.4 and {S_{sb}} from SY model is sufficient for fair comparison. This result also implies that the reconstructed images with ϕ =1 are far from *AVLL* for both SY and Watson's models. It is noted that perceptual error smaller than (ϕ_{avll} S_{sb}/2) is considered as zero and that JND_MSE is zero if $\phi = \phi_{avll}$.

Data in Table 3 are obtained for 512x512 Lena as follows: ϕ_{avll} =0.4 is used on SY model and bit rate, PSNR, JND_PSNR and JND_MSE (to be define later) are calculated and decoded image is saved for $S_{cd}(Lena, Lena')$ (mean CDVLL) measured at a later time. The procedure repeated again using Watson's model with ϕ_{avll} =0.15. Now, bit rates are controlled to the same as those for SY model and Corresponding data are obtained for fair comparison.

Additional CDVLL measurements are made for 512x512 F-16 as well as 512x512 Salesman. For F-16 at bit rates of 0.8, 1.5 and 2.0, the corresponding $S_{cd}(F16)$ are 93/109, 58/60, 39/47 cm, while $S_{av}(F16)$ are

$$\frac{0}{6}/\frac{0}{6}, \frac{2}{6}/\frac{0}{6}, \frac{5}{6}/\frac{4}{6}$$

respectively. For image Salesman at bit rates of 0.8 and 1.1 bpp, the corresponding $S_{cd}(Salesman)$ are 62/78, 44/49 cm and $S_{av}(Salesman)$ are

$$\frac{0}{6}/\frac{0}{6}, \frac{4}{6}/\frac{3}{6}$$

respectively.

Above experimental results indicate that reconstructed images by SY model consistently yields better subjective fidelity in terms of VLLCVD as well as JND_PSNR (or JND_MSE) criteria than those by Watson's model at various fixed bit rates.

Table 3. Comparison of SY model with ϕ =0.4 and Watson Model ϕ =0.15 with 512x512 Lena

SY / Watson	bpp	JND_ PSNR	PSNR	JND_ MSE	Mean CDvll S_{cd}
Map1	0.0069	10.50	7.58	5794.7	
		11.02	7.92	5143.0	
Map2	0.0145	18.67	15.88	882.88	
		18.94	16.65	829.21	
Map3	0.0215	20.71	19.51	552.01	
		20.89	19.65	530.37	
Map4	0.0286	22.97	21.61	328.44	
		23.21	21.86	310.77	
Map5	0.0370	24.95	23.41	207.77	
		25.04	23.51	203.72	
Map6	0.0537	27.71	25.75	110.23	
		27.73	25.84	109.79	
Map7	0.0897	31.12	28.34	50.196	
		31.02	28.39	51.397	
Map8	0.1607	35.34	31.06	19.017	383.75
		35.18	31.26	19.712	389.50
Map9	0.2758	40.04	33.77	6.4367	245.00
		39.58	34.03	7.1570	282.75
Map10	0.4789	45.29	36.20	1.9234	163.42
		44.60	36.68	2.2564	194.33
Map11	0.8777	52.01	38.62	0.4094	106.92
		50.70	39.27	0.5531	121.83
Map12	1.8038	83.51	42.56	0.0003	19.83
		57.53	42.42	0.1148	67.25

6. Conclusions

In this paper, we propose a subjective fidelity criterion called VLLVCD, which is based on the SPS (Same Position Swapping) technique and VLLCVD (Visually LossLess Critical Viewing Distance) process. The VLLCVD SFC provides two scores S_{cd} and S_{av}, that are more strict and precise for evaluating the fidelity of a decoded image. We also demonstrate the application of the proposed VLLCVD FSC in the comparison of visual models. The results shows that SY model performs consistently better than Watson model for a wide range of image fidelity.

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Biography

Day-Fann Shen received his diploma in EE from Taipei Institute of Technology, Taiwan in 1976. MS and PhD in Computer Engineering from University of Cincinnati and North Carolina State University in 1983 and 1992 respectively. 1988-1992 he worked for IBM, Research Triangle Park, NC. Since 1992 he has been with EE department, Yunlin University of Science and Technology, Taiwan. His work has primarily focused on human visual property, image/video processing/coding and watermarking. He is a member of SPIE and IEEE.