A Predicted Compensation Model of Human Vision System for Low-light Image

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***Abstract*—Human visual perception determines the evaluation results of imaging system. This paper presents a nonlinear contrast resolution enhancement based on human vision system (HVS) characteristics. As human visual system has the characteristics of space and time threshold, the tool of gray flattening is used to analyze the gray scale distribution of low-light image. With the determination results of contrast resolution in low-light image, a nonlinear compensation method based on HVS characteristics is presented for improving visual low-contrast resolution. A compensation model prediction for machine vision system is also established to quickly obtain the appropriate image. Experiments show that the algorithm achieves simultaneously brightness and contrast enhancement for the low-light image, which not only improves background luminance, suitable for human visual observation, but also enhances the contrast of the image with more obvious layering.**

Keywords-visual features; contrast resolution; nonlinear compensation; prediction modeling

I. INTRODUCTION

The purpose of image enhancement is to improve the visual effect of an image using hardware-enhanced technology, or convert image into a more suitable form to analysis and process by person or machine system. By the interference and influence of the factors, such as the external environment, equipment, images obtained in the dark vision often have low and concentrated gray scale, result in a small dynamic range and low contrast. Different from ordinary images, due to the low illumination of scenery and goals and low sensitivity of imaging devices, low-light level images have the feature of low resolution and low signal noise ratio. It is easy to introduce gaussian white noise and quantum noise, leading to human visual resolution and recognition ability of the machine system is decreased.

Image enhancement in the field of the computer uses contrast enhancement technology, mainly linear stretching, histogram equalization, unsharp masking in the spatial domain, filtering in the frequency domain and so on. However, these methods do not pre-determine the input image gray (background illumination) type, the algorithms have less intelligence and adaptability [1]. Traditional methods can produce a certain image enhancement effect, and also inevitably bring in the relevant noise enhancement; based on computer statistical characteristics, the common assumptions that noise is irrelevant additive white gaussian noise are unreliable and inconsistent for correlation noise in the natural image is random, and has a positive-definiteness [2]. The methods mentioned above are not suitable for enhancing the low-light level images with low signal-to-noise ratio, for human visual perception of image quality is poor [3]. In [4], it proposes a method of using gray stretching section to enhance contrast and suppress white noise, but the algorithm is complex, bad adaptivity and not suitable for real-time system.

According to the average brightness level, the methods based on Retinex algorithm are put forward to reduce image degradation caused by inequality light. It effectively enhance the interested region. But there are the problems that enhanced grayscales of part pixels are out of range, with the result that the vision effect is dark and color distortion leads to important information is lost at the same time. And what is more serious is that convolution operation affects the real-time system in video processing [5].

The main body in evaluating image processing result is human eye. Under the premise of the wavelet noise reduction, the effect of visual perception is considered. This paper presents an image enhancement method based on human vision characteristics which is the compensation for contrast resolution and more suitable for low-light image.

II. JND COMPENSATION

A. Human Vision System

Vision system has evolved to be a highly complex mechanism for visual perception. As an ideal sensor of the image information in the visual system, human eyes also exist the restrictions of time response, spatial response and resolution in perceiving images. In psychophysical experiments, visual acuity varies with both spatial and temporal frequencies simultaneously. Human visual system has a number of basic features, such as contrast sensitivity, multi-channel structure, masking effect and visual non-linear laws (Weber, Fechner, Rolle) and so on. The result of vision perception is related to HVS property in image quality evaluation [6].

Human vision is a multi-channel structure, which divides the input image into different sensory components. Each channel has its own sensory threshold (called the visual threshold). Combining human visual perception phenomenon with the results in physiology and psychology experiments, a variety of masking effects existing in human vision is found, mainly HVS brightness, edge, texture of the shield. Shielding effect in the space domain and time domain is the main reason for the visual threshold. The study is commonly contrast sensitivity, which is also known as the space modulation transform function (MTF) in human visual system. Human vision is sensitive to the contrast and can only sense a signal that the contrast is above a certain threshold with respect to signal frequency. The reciprocal of frequency threshold is contrast sensitivity which is a function of spatial and temporal frequency. And the relative amplitude of human vision showed a linear band-pass filter characteristic in space and time frequency domain [7]. The space perception ability of human vision has a great relationship with the relative brightness between the target and background [8].

It is believed that human vision has different sensitivities to different grayscales, usually the most sensitive to medium intensity and not sensitive to high intensity and low intensity.

B. *Just-noticeable-difference Threshold*

The perception of the human visual system depends on the relative changes in intensity of background, rather than absolute brightness values, so the contrast is that the relative change in brightness measurements.

According to Weber-Fechner's law in relative contrast sensitivity experiments, the human eye's ability to observe the brightness variation is limited and the smallest brightness change of L_t-L_b that can be detected are different in different background brightnesses. Within a certain range of background grayscale L_b in a nearly continuous uniform distribution (moderate intensity), define the constant as follow:

$$C_w = \frac{L_t - L_b}{L_b}, \tag{1}$$

where L_t refers to target brightness, L_t-L_b refers to the least perceptible difference and C_w reflects visual acuity to the gradational light intensity which is also known as relative sensitivity threshold [9]. Contrast threshold is a non-linear function on both background brightness and spatial frequency. Weber's law is based on HVS structure property. Using psychophysical methods to determine the result, contrast perception threshold of human eyes is the minimum sensitivity that required when the target just can be perceived by eyes.

The test of CSF function is commonly determined by luminance grating and cathode ray tube (CRT) monitors, the contrast is defined as Michelson contrast C_M:

$$C_M = \frac{L_t - L_b}{L_t + L_b}\ , \tag{2}$$

where L_t refers to target brightness and C_M refers to the rate of contrast variation under different background grayscales L_b [10].

However, the above descriptions of physical contrast have some definitional deficiencies; for instance, contrast is uncertain in (1) when the background grayscale is 0, contrast variation rate is non-linear in (2), especially the mensuration of physical contrast in the low background grayscale is greater than in the high grayscale background.

Contrast sensitivity studies the relationship between spatial frequency and the background grayscale in moderate intensity, not concerned with the classification of scotopic vision, mesopic vision, photopic vision. Here the concept of just noticeable difference (JND) is quoted to represent subjective contrast resolution which is a psychological quantity that can be measured physically.

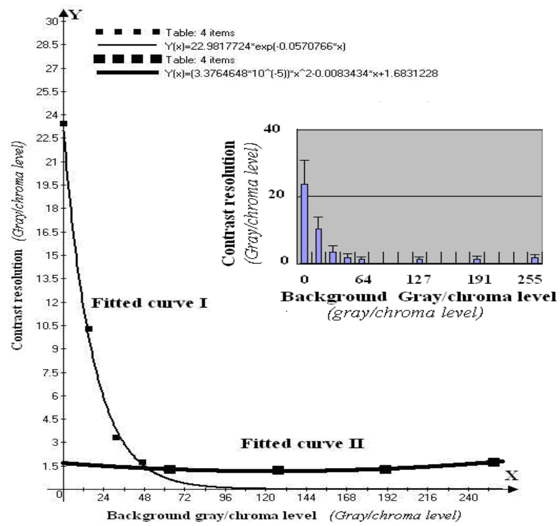


Figure 1. The contrast resolution variation of human vision with criterial gray level

In Fig. 1, due to visual adaptation, the corresponding contrast threshold value that human eyes can just distinguish between brightness differences is a constant in the gray-level range form 64 to 190. When the background grayscale is strong or weak, the contrast resolution threshold of human eyes will increase, and the ability to distinguish the differences in certain background brightness reduces. But Weber's law defines contrast resolution threshold within a constant range.

According to human visual physiology, human vision cell with visual perception function to images in high gray-level and low gray-level environment are different. Therefore the measurement of JND is divided into scotopic vision, photopic vision,and the following results is received:

$$Y(\mathrm{x}) = \begin{cases} 22.98e^{-0.057\mathrm{x}} & 0 \le \mathrm{x} \le 47 \\ 1.683 - 0.0083\mathrm{x} + 3.376\times10^{-5}\mathrm{x}^2 & 64 \le \mathrm{x} \le 255 \end{cases}, \tag{3}$$

where $Y(x)$ is human visual contrast resolution, x is background grayscale. The relationship between $Y(x)$ and the different background gray x is non-linear in different background conditions. The nonlinear contrast resolution in scotopic vision is the negative exponential function with the change of background intensity [11].

Different from contrast sensitivity, JND is an appropriate contrast unit. Psychophysical experiments show that JND is of the high (low contrast) in low intensity background and is also of the high in high intensity background, showing a concave shaped distribution in JND curve.

JND refers to the minimum difference that the human visual system (HVS) can perceive, and plays an important role in perceptual image and video processing.

C. Non-linear contrast resolution compensation

In the scotopic vision, information in an image is not fully mined by human vision due to the limit of low contrast resolution. If this constraint of non-linear contrast resolution can be compensated, the ability of human contrast resolution can be greatly expanded, especially contrast resolution in the environment of scotopic vision.

If an adjacent-level original gray-scale difference is expanded to JND, human visual resolution can be compensated. Compensation method makes a kind of gray difference that can not be distinguished originally become appropriate for human visual resolution. The amplification of the gray-scale difference is bigger, the contrast ratio is higher and then the image can be clearer. The extreme of compensated gray scales adjacently is black and white, respectively 0 and 255.

The definition of contrast resolution compensation in scotopic vision is as follows:

$$TG(x,y)=\begin{cases} og(x,y) & og(x,y)=0 \\ k\displaystyle\sum_{i=0}^{og(x,y)-1} JND(i) & og(x,y)>0 \end{cases}, \tag{4}$$

where k refers to the compensation factor, $TG(x,y)$ refers to compensated gray value, $og(x,y)$ refers to original gray value, with the range changing from 0 to 255. Here i is the background intensity, refers only to adjacent pixel gray value in an image and has the maxium value of $og(x,y)-1$. $JND(i)$ equals to $Y(x)$ in (3), and represents exactly the just-noticeable difference that can be distinguished under the background gray-scale of i. As a gray-scale image detection tool, the method of gradually flattening gray spectrum is cited in [12], the spectrum analysis is used to mine low-light image information. It can dig out the information that hidden in image intensity artificially, or submerged by the strong background and had only a small number pixels of a certain grayscale.

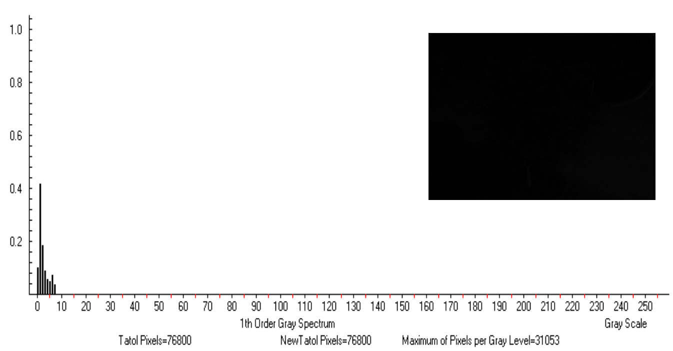


Figure 2. The gray spectrum with the order 1^{th} flattening of orignal image

Where X axis represents 8-bit gray-scale, Y axis represents the percentage of the pixels number of various grayscales in the total pixels number. In original image*(a)*, As the small pixel distribution probability, it is difficult to distinguish the grayscale of 9. But the hidden information can be extracted by the mining tool of gradually-flattening gray spectrum.

In Fig. 3, it shows the distribution probability of every grayscale and the relative change of gray level in compensated image. And after compensating the original image in Fig. 2, human eyes can distinguish trees and roads of compensated image in Fig. 3. Compared with the grayscale information in original image, the total pixels number of every grayscale in Fig. 3 remains unchanged, but grayscale difference and contrast is larger, the overall brightness level increases and contrast resolution is effectively improving.

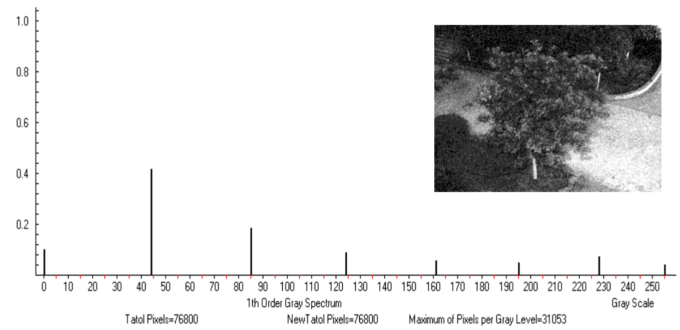


Figure 3. The gray spectrum with the order 1^{th} flattening of compensated image (k=1.9)

JND method produces a noticeable variation in visual perception. The method of non-linear JND compensation mentioned above breaks the limitation of contrast resolution, but the best compensation result should be determined by human. The compensation depth determines the visual effects.

III. PREDICTION MODEL

Subject evaluation based human visual system is on the basis of certain assumptions (cognitive test). Brightness, contrast and the amount of information contained in images are widely used in evaluation, the three parameters extracting form the visual system is in focus. The best image quality assessment model is established by approximating integrated function of the brightness, contrast and other key information that weighted by the human visual perception [13]. In the classical objective evaluation, Average gray (AG) reflects the average brightness of the image, visual effect is suitable if it is moderate. Average contrast (AC) reflects the image clarity, the greater variance of contrast make the details more clearly. Therefore, the physical quantities of *AG* and *AC* meet the basic requirements of human vision characteristics and are consistent with subjective evaluation. Information entropy (*IE*) is also an important indicator to measure the richness of image information that how much the average amount of information is contained in the image. The larger the information entropy, the greater the amount of information carried in the image. The richness of the information is also an objective evaluation criteria in image quality assessment (IQA).

A new method to evaluate image quality that depends on the visional perception property has been proposed by the research on three factors (*IE, AC, and AG*) in observing image.

In Fig. 4, the framework incorporates *JND* compensation into three components; *IE*, *AG* and *AC* are used to establish the model of image perception process. The purpose is providing no-reference IQA results for low-light images, which have good consistency with subjective perception value.

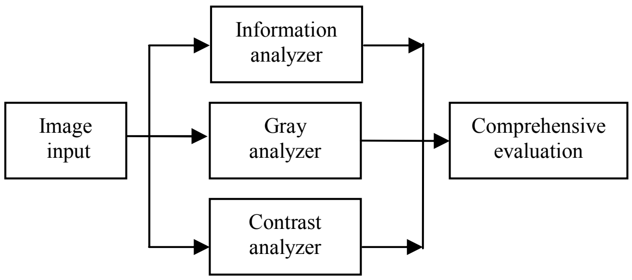


Figure 4. The framework of no reference image quality assessment model

A comprehensive optimal quality assessment function (CAF) is designed to evaluate the result of compensation. The best quality image is corresponding to maximal value of CAF.

$$CAF = IE^{\alpha} \times AC^{\beta} \times NGD^{\gamma} \ , \tag{5}$$

where NGD denotes normalized gray distance (NGD). It can be obtained by the following formula:

$$NGD = \frac{(127.5 - dist(127.5 - AG))}{127.5} \ , \tag{6}$$

where dist (·) is distance operator. By a large number of experiments, define the weights that $\alpha = 1$, $\beta = 1/4$ and $\gamma = 1/2$ respectively. Therefore, if the *CAF* value of compensated image is the maximum, the compensation value of *k* is the optimal parameter (K_{op}).

In computer graphic, the efficiency and real-time of the algorithm is an important factor that need to be considered in optimizing processing results. While combining the human vision with machine vision, the following aspect should be considered: how to build a reliable algorithm accurately and realize it quickly and smoothly [14]. The former depends on adopted processing algorithm structure, which refers to machine vision psychology, researching how to achieve it effectively to get closer to human visual psychology. The latter comes down to the prediction model that achieves machine vision images more efficiently and reliably in video.

Subjective evaluation of image quality depends on the chosen compensated parameter, while the factor is the best; the optimal quality image is obtained. By extracting the original gray value of image information directly to obtain reasonable compensation parameter, the method improves the possibility of optimizing the algorithm in video processing. Through different compensation experiments, it is found that different average grayscale of the original images have different best *k*-value K_{op}. Therefore the prediction model based K_{op} can be established.

The average gray values of the original image (a0), (b0), (c0) are less than 47 and in the scotopic vision. Compared with the best factor K_{op} in the integrated function of *CAF*, predicted parameter (K_{pp}) obtained by fitting compensation model is simple and convenient, which is the function of *AG0*. Here K_{pp} denotes predictive value of compensate factors; *ER* denotes the difference between K_{op} and K_{pp}.

TABLE I. PREDICTION MODEL WITH K_{PP}

	Natural Scenery	**Car**	**Human**
AG0	3.2	5.9	10.3
K_{op}	1.15	0.65	0.45
Model	K_{pp}=3.586/AG0+0.023		
K_{pp}	1.14	0.63	0.37
ER	0.01	0.02	0.08

Form the original image with different average gray value, the method gets fitting points and linearizes them to build a prediction model as following figure:

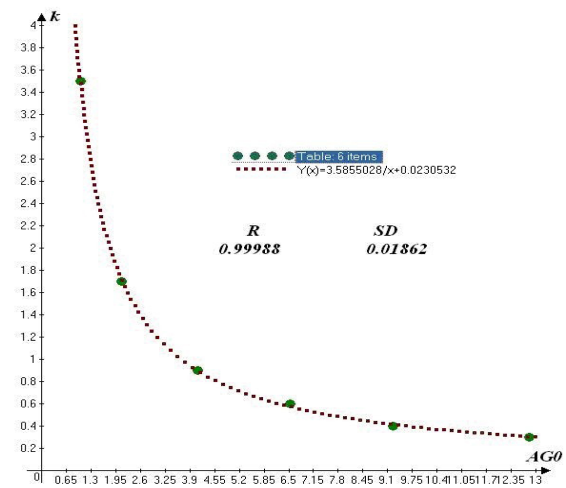


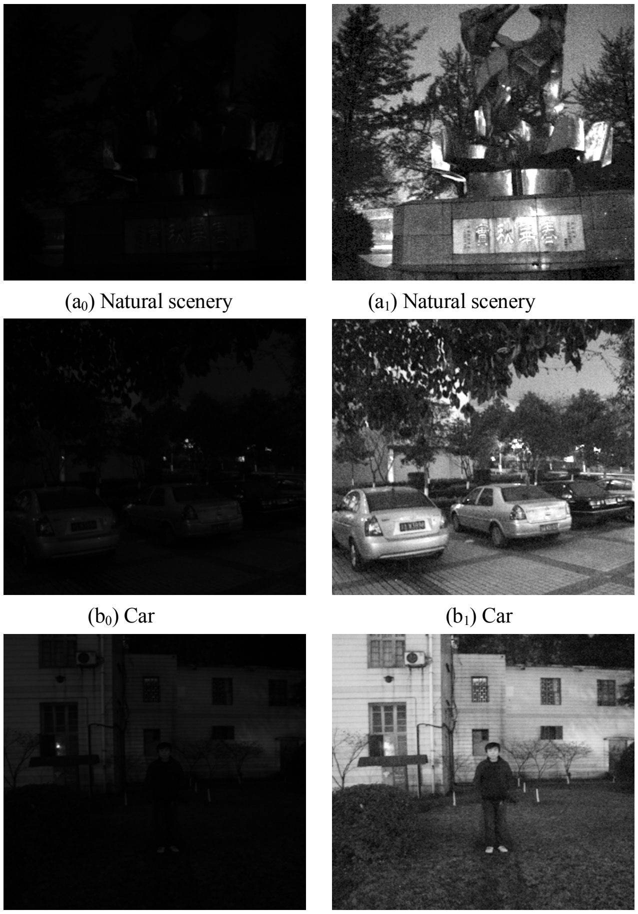
Figure 5. Fit compensation curve(R: correlation coefficient)

In Table 1, verification results of predicted compensation show that the difference of K_{pp} and K_{op} is in allowable error range, the correlation coefficient *R* satisfies the requirement of linear fitting. Therefore, the approach of predicting K_{op}-value simplifies the process to produce optimal perception quality, the feasibility of the method is improved.

IV. EXPERIMENT RESULT AND DISCUSSION

Since the contrast resolution is low in scotopic vision, Partial information of the low-light images can not be perceived by human eye and the visual effect of compensation is shown in Fig. 6. Compensated image is different form the original image with a large dynamic range of gray level and contrast. (a_0), (b_0), (c_0) are original image in the scotopic vision and (a_1), (b_1), (c_1) are the compensated image with various predicted *k*-value respectively, human visual system can perceive the hidden information of the image.

As it is shown in Table 2, low contrast and gray level of the original image is greatly improved by nonlinear optimization compensation and the increase of brightness and contrast is at the expense of the amount of information, the whole visual range of compensated image reach to the photopic vision.



(a_0) Natural scenery (a_1) Natural scenery

(b_0) Car (b_1) Car

(c_0) Human (c_1) Human

Figure 6. Compare the orignal image(a0,b0,c0) with kop compensated iamge(a1,b1,c1)

TABLE II. THE PARAMETERS COMPARISON OF COMPENSATED IMAGE AND ORIGNAL IMAGE

	IE	AG	AC	K_{op}	CAF
a_0	3.08	3.25	0.69		0.45
a_1	3.00	83.30	14.82	1.15	4.75
b_0	3.86	5.89	1.25		0.88
b_1	3.84	85.38	14.65	0.65	6.14
c_0	4.44	10.28	1.22		1.32
c_1	4.43	85.87	8.31	0.45	6.18

In addition, for the vision can hardly distinguish the visual differences in images that compensated image and predicted respectively, while the predictive parameter is fairly close to the value of K_{op}, it can be considered that image quality is the optimum. *AG* of image is important in predicted model. It can be conclusion that average gray of the image which comes near to 127.5 grayscale is the best.

V. CONCLUSION

The prediction model of compensation has the following characteristics:

(1)It enhances the natural areas and local features of the image and makes full use of the image intensity characteristics and spatial correlation of the image information to improve output image more smooth and natural;

(2) Subjective quality assessment is the gold standard. As the compensation parameter based *JND* is directly linked to visual contrast resolution, subjective perception is introduced in the compensation method, and it achieves a better visual effect;

(3) The proposed prediction models is designed to optimize the function of *CAF (k)* based on *NR-IQA* model, so the method has the characteristics of adaptability and effectiveness.

The visual perception model can be used to assess image quality taken from scotopic vision. The results of predictive compensation are well consistent to subjective assessment. The prediction algorithm based on *JND* compensation is designed for video processing and has been realized in hardware platform for real-time applications.

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