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Retinex theory for color image enhancement: a systematic review

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ABSTRACT

A short but comprehensive review of Retinex has been presented in this paper. Retinex theory aims to explain human color perception. In addition, its derivation on modifying the reflectance components has introduced effective approaches for images contrast enhancement. In this review, the classical theory of Retinex has been covered. Moreover, advance and improved techniques of Retinex, proposed in the literature, have been addressed. Strength and weakness aspects of each technique are discussed and compared. An optimum parameter is needed to be determined to define the image degradation level. Such parameter determination would help in quantifying the amount of adjustment in the Retinex theory. Thus, a robust framework to modify the reflectance component of the Retinex theory can be developed to enhance the overall quality of color images.

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1. INTRODUCTION

The topic of image enhancement has drawn attention for being an essential approach to significantly improve images quality [1-5]. In this regard, the main purpose is to consider specific criteria to improve the quality of the image in a way that enhances the visual appearance of the resulting image when compared to the original image [6]. Add to this, the radiometric corrections to eliminate the effect of the radiometric errors that could exist even with the use of a calibrated imaging system to acquire the image. Examples are the non-uniform illumination, the impressive reduction transported by impressive sprinkling, and the preoccupation.

To date, a small number of methods based on single-scene image improvement is developed to provide a remedy for the issue of uneven and non-uniform illumination. The Homomorphic Filter method, denoted by (HF), can enhance the quality of the image by manipulation the illumination and enhance the dynamic compression of the image. Yet, the issue of color distortion is unavoidable. Furthermore, HF technique tends to bleach the image and its tonal rendition is poor [6-8]. On the other hand, the Histogram Equalization method, denoted by (HE), improves the intensity distribution of the image [6, 9-12]; however, the brightness and color of the original image are hardly preserved.

Color perception approaches are also proposed to solve the uneven intensity distribution issue. Here, the Human visual system (HVS) is utilized to apply the required illumination corrections in each and every pixel of the defect image. Figure1 shows a basic cross of the human eye. The retina of the human eye responds to very low levels of illumination through scotopic vision mode. Here, the rods of the retina become active to handle the low level of light brightness where the capability to distinguish colors vanishes. Other vision modes of human eyes are photopic where the cones are active and mesopic where the cones and rods are both active. Mesopic vision can be identified as a mixture of photonic and scotopic vision and happens under the circumstances when the level of illumination is low but not dark lighting situations as in most of the work offices [13, 14]. Hence, at these circumstances of light levels, the pattern information contributed by the rods remains unclear. Thus the human visual observation (HVS) cannot recognize the color efficiently [15, 16]. Yet, HVS is capable of observing the colors that are related to the sight i.e. color constancy. Hear, achieving invariance level in a certain illumination situation is feasible for many modern imaging applications. Examples include the contrast improvement in images that are dynamically created or the correction of white balance in the images that are produced by commercial cameras. Additional implementation model arises in the applications of remote sensing that involve image recognition.

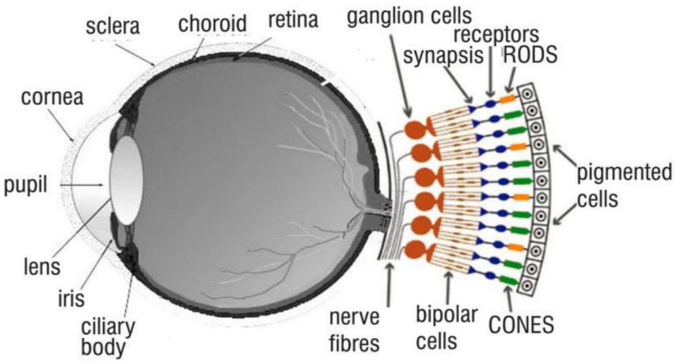

Figure 1. Basic cross of human eyes showing the rods and ones

Retinex Theory is fundamentally based on the visual perception property of human being. The theory is originally proposed by Land and McCann [6-8]. In their work, they tried to explain the HVS as a mixture of processes in both the cortex and the retina. The Retinex theory works in the illumination conditions that spatially vary with both of the color and the intensity. In addition, the insensitivity of the visual perception of the human being to the illumination that slowly changes is also observed by Retinex. Additional work by Edwin Land and McCann can be found in the study in [17].

Today, the Retinex theory has been applied in numerous different applications. Each and every one of those applications is particularly able to be adapted with specific tasks. Those tasks include the four main criteria which are: (1) contrast enhancement, (2) color balancing, (3) shadow removal in consumer electronics and imaging and (4) dynamic range compression. In this context, different assumptions are considered while applying the Retanex theory that in turn leads to various implementation results. Here, the assumptions of the theory are selected based on the considered applications as well. Furthermore, this theory, and in order for achieving images based on a reflectance correlation in the bandwidth of a wavelength, employs the function and the structure of the "retina and cortex" [6].

The reminder of this paper is arranged as follows: the theory of Retinex is presented in Section 2. In Section 3, Retinex theory types are further discussed where a thorough review has been made on each type. Strength and weakness of Retinex types are also highlighted. Section 4 presents the discussions and Section 5 concludes the review.

2. THEORY OF RETINEX

Retinex theory is first introduced by Land and Mc Cann as a model of "Human Visual Perception (HVS)" as mentioned-above [18]. In their work, the main consideration was based on the assumption that an acquired image is achieved through the combined action of the components of the reflectance and the illumination. Here, the illumination component captures all the types of light sources. Thus, the reflectance component can be isolated by excluding the illumination component from the acquired picture or image. Furthermore, the component of the reflectance handles the frequencies with high levels whereas
the frequencies with low levels are captured by the illumination component.

A "Single-Scale Retinex" (SSR) [1] and a "Multi-Scale Retinex" (MSR) [19] were proposed by Jobson et al. Both of these methods apply a surround function on the input image. Consequently, the illumination level is estimated on the output image by utilizing the reflectance natural logarithm. However, a color distortion effect may be induced in the obtained image that represents a challenge in (SSR) and (MSR) methods. To fix this issue, a "Multi-Scale Retinex with Color Restoration" (MSRCR) was proposed [3]. Here, with (MSRCR), a step to handle color distortion and restoration using the color ratio of the red, green and blue (RGB) channels, is included. Yet, this technique tends to lose image details, especially in the bright region due to the globally applied mapping curve. To this end, the Retinex theory is basically based on the idea that the color perception is based significantly on the characteristics of the human vision neural system. Add to this, the term "Retinex" is formed by Land and McCann through the use of the two main root words "retina" and "cortex"; here, the vision process fundamentally relies on both the retina and cortex. Next, we refer to the following indication: when recognizing a color, the additional red color of a tungsten lamp is not identified by the eye. Hene, this indication was utilized by Edwin Land to introduce the Retinex method [20].

To this end, the Retinex approach, and since formulated by Land/ McCann, has become one of the popular approaches in image enhancement. The classical theory of Retinex has been modified and adaptively changed to meet specific criterias for various applications. The next section thoroughly explains the methods that had been derived from the original work of Land/ McCann.

3. TYPES OF RETINEX

Numerous Retinex approaches have been published over the years where they can be categorized into four main categories as follows, refer to Figure 2.

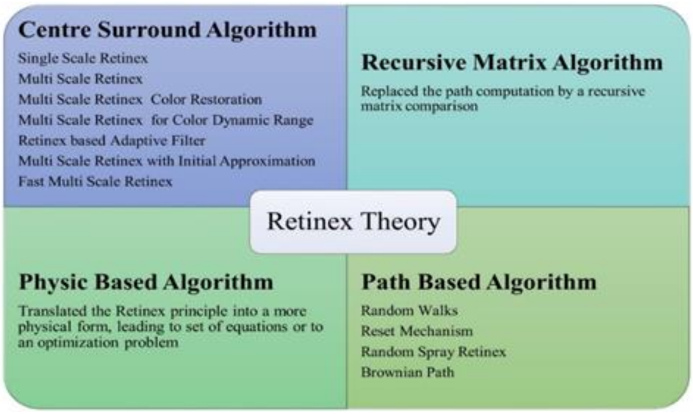

Figure 2. Types of retinex

3.1. Path based algorithm

The approach of the Path-Based Algorithm is to multiply the ratios along random walks to obtain the lightness of each pixel. The studies of Land and McCann [18, 21], are summarized here with the recent implementations such as those presented in [22, 23]. The path based algorithm is divided into few categories as follows:

3.1.1. Random walks

The fundamental approach f this category is to examine the entire image by walking along all the 1-D paths. Accordingly, the relative relation between the light and shade is evaluated. Furthermore, the reflection values at each pixel are obtained; here, these values depend on the average light to shadow ratio of all the pixels of the image [18, 20].

Land and McCann concluded from several experiments that edges are the main features which are insusceptible to illumination and therefore be used as the basic material to attain color devotion [18]. Also comprehended the luminance ratio edge between two nearby points maintained the existing edges but the gentle slopes caused by the non-uniform illumination were eliminated. Therefore, the lightness values could be obtained by comprehensively exploring the luminance ratio in the image, see Figure 3. Here, at each pixel where the lightnesses are evaluated, Retinex takes into account all the probable paths which have started and ended at random points and these pixels. In this context, this lightness along a path represents the average of the ratios between the intensity amounts of each succeeding edge points. Thus, a threshold is considered such that these ratios are set to be unitary if the difference between edge points is less, and hence, elimination the impact of the non-uniform illumination on the process.

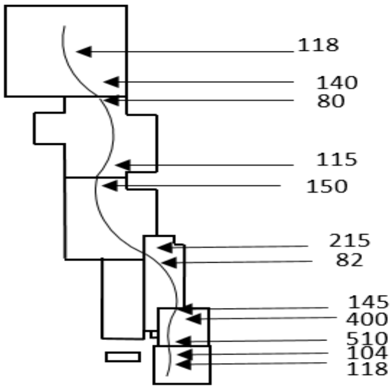

Figure 3. The random walk retinex mechanism by Land/McCann [6]

Then, to evaluate the lightness along all possible paths,

$$L(x) = \frac{\sum_{k=1}^{N} L(x;yk)}{N} \quad (1)$$

Noted that L(x; y_k) would be evaluated as:

$$L(x;\ yk) = \sum_{t_k=1}^{n_k} \delta \left[log\ log\ \frac{I(x_{t_k})}{I(x_{t_k}+1)} \right] \quad (2)$$

Where γ_k represents the considered path and L(x; y_k) represents the relative lightness of a pixel x with respect to a pixel y_k. Here, with a contrast threshold (t) is considered

$$\delta_{(s)} = \begin{cases} s, & if\ |s| > t \\ 0, & if\ |s| < t \end{cases} \quad (3)$$

3.1.2. Reset mechanism

The aforementioned definition was improved in the reset mechanism. This approach ensures to consider the regions that include the highest values of luminance such that all the paths emanating from these regions are counted. However, areas that consist of the highest reflectance are not easily distinguishable. The development of this technique is droved based on the assumption that the initial ratio is given. Then, the signal ratio is calculated between the first and the second receptors and subsequent by the ratio between the second and the third receptors, and so on (4) states the expression by which the rest mechanism of Retinex is formulated.

$$\forall j = 1, \ldots, n_k - 1, \sum_{t_k=j}^{n_k} \delta \left[log\ \frac{I\left(x_{t_k}\right)}{(x_{t_k}+1)} \right] \leq 0 \quad (4)$$

Here, the average is evaluated along the paths such that the overall summation consists of non-positive partial summations as shown in (4).

3.2. Recursive matrix algorithm

The Recursive Matrix Algorithm was initiated by Frankle and McCann [24]. Here, a recursive matrix comparison approach is utilized as an alternative to the original path computation [24-26]. This algorithm crucially depends on the calculation of the optimum number of iterations; that is the number of visits to a pixel's neighbors. Hence, it is considered as a limitation since this parameter is hard to be determined and can essentially affect the final result [27]. Figure 4 show implementation of Brownian Path Algorithm.

foreach chromatic channel ***do*** compute sequentially each

pixel as follows:

generate N random points in the image and

foreach random point ***do***

generate a path by 2_M random mid-point displacement;

follow the generated path and

foreach pixel ***do***

calculate the new chain function value (Knew);

if Knew > threshold then Kold . Knew;

if Knew > 1 then Kold = 1;

(a pixel with an higher lightness value has been visited)

newChromaticPixelValue = average of all N final values Kold;

(1 foreach random path)

Figure 4. Implementation of brownian path algorithm

3.3. Physics-based algorithm

This algorithm represents one of the main Retinex division with a physical form that is presented by a set of equations [28-30]. In this algorithm, image intensity is denoted by I, the reflectance is denoted by R, while L refers to the incident illumination intensity. Consequently, the equation is presented as:

$$I = R \cdot L \tag{5}$$

In this regard, a different approach to evaluate the illumination, as well as the reflectance, was proposed by Horn. In his approach, Horn utilizes the logarithm of the image intensity such that,

$$\log I = \log R + \log L \tag{6}$$

The main concept of Retinex Physics-based algorithm is that illumination might contain varies smoothly over the image. On the other hand, sharp discontinuities are shown only during reflectance changes. Laplacian function stated in (7) was also utilized by Horn to introduce “Poisson equation”.

$$\Delta \log I = \Delta \log R + \Delta \log L. \tag{7}$$

Accordingly, Horn proposed another technique that applies the threshold operator T in-order to remove the second term of (7) that is constant, and thus provided a direct relation between R and I as shown in the (8).

$$\Delta (\log R) = T (\Delta \log I) \tag{8}$$

The “Poisson equation” successfully estimates the value of reflectance. The result is normalized by assuming one point in the image as minimum that has the ability to reflect all the lights that assumed to be white. This equation is also denoted by “Poisson-equation-type Retinex algorithm” in [31]. The study by Kimmel et al. [32] also proposed the variation models for Retinex. In this context, the approach considers the illumination to be smooths. Thus, it inserts the variation model in a similar manner to the Horn’s model. Active multiresolution solution to various problems are also introduced by the authors.

4. DISCUSSIONS

4.1. Summary of the research

The main objective of this study is to identify the potential of Retinex algorithm in image enhancement applications. A systematic search of the literature revealed the classical approaches of Retinex algorithm such as in Path-Based and Recursive Matrix Algorithms. These algorithms are among the first findings by Land and Mc-Cann where the implementation of both techniques are based on the path computation. The more advanced approach has been implemented in the latter algorithm where the path used in the first algorithm was replaced with the recursive matrix comparison. Retinex techniques are simplified in Figure 5.

Techniques	Recursive Matrix	Path Geometry	Fast	Real Time Application	Center Surround	Appearance	Dynamic Range	Enhancement of 8 bit color	"Halo" effect	Random Walks
Path Based Algorithm	/	X	/	/	/	/	/	/	/	X
Recursive Algorithm	X	/	/	/	/	/	/	/	/	X
Random Spray Retinex (RSR)	/	/	X	X	/	/	/	/	/	/
Single Scale Retinex (SSR)	/	/	/	/	X	X	X	/	/	/
Multi Scale Retinex (MSR)	/	/	/	X	X	X	X	/	/	/
Multi Scale Retinex Color Restoration (MSRCR)	/	/	/	/	X	X	/	X	/	/
Multi Scale Retinex with Initial Approximation (MSRIA)	/	/	/	/	X	X	/	/	/	
Multi Scale Retinex with Wide Dynamic Range (MSRWDR)	/		/	/	X	/	/	/	X	/
Retirex based Adaptive Filter (RAF)	/	/	/	/	X	/	/	/	X	/
Fast Multi Scale Retinex (FMSR)	/	/	X	/	X	/	/	/	X	/

/- denotes the technique exhibit the selected criteria

X- denotes the technique does not exhibit the selected criteria

Figure 5. Retinex methods techniques

The complexity of generating a path that includes a number of paths to be used, and their length are mainly solved in the Recursive Matrix Algorithm. However, the final results of the algorithm highly depend on iteration that indicates the time pixel boundaries in the image and determine the number of the neighbors to be considered. Hence, the objective of image enhancement is subjected to this crucial parameter which adds more complexity to the enhancement task itself.

The Retinex theory has been further improved by including the neighborhood or surround function of each pixel. The limitations in SSR such as color rendition and dynamic range compressions were improved by the MSR function. To date, numerous works of literature have reported on the modifications of the Retinex theory based on this MSR function as in [33-35]. The trade-off between preserving color distribution and suppressing halo effect on the image is still unresolved. The weighted function needs to be designed such that the halo effect will be eliminated while the nature color of the image will not be distorted. In addition, noises of the image should not be enlarged.

The optimization factor was introduced in the Physic Based Algorithm where the new factor plays a major role in obtaining the enhanced image without compromising the natural color of the image. The improvements that has made to the Retinex theory has led to the exploration of the new possibility in enhancing the image without introducing halo effect while maintaining color distribution of the image.

4.2. Applications of retinex

4.2.1. Color balancing/restoration

Color balancing and color restoration have been presented and described through different ways and models by many researchers [1, 2, 36-41]. Retinex theory is always there to help for achieving these objectives. In [42] a new spectrum shape elements approach to handle the non-isopalmitic deviation in illumination was presented. This approach was implemented and tested for floor and hyperspectral images. While in [43], MSR method had been used to examine the visual system of human being and illustrates how it perceives color. A slightly different approach of MSR is reported in [44]. In this regard, the characteristics of the nighttime image are utilized to modify Retinex. The tradition algorithm was replaced by a customized sigmoid function using an improved framework. In summary, the Retinex theory maintains the values of the RGB color components of each pixel of the image and estimates the reflectance of each point.

4.2.2. Shadow removal

Retinex theory has been known as one of the solutions in shadow removal. In this regard, the SSR algorithm is utilized in the study in [45] where the shadow of an image with a single color was eliminated. Firstly, shadow and non-shadow regions are evaluated by SSR. Here, and by considering the features of SSR, a robust dynamic compression is achieved using a limited scale filter and thus the shadow is removed. While in [46] MSRCR was utilized for shadow removal. Here, the shadow area is observed using a detection approach that is based on a gradient edge which is combined with 1-D illumination invariant image. Subsequently, the Retinex algorithm is used to remove the shadow where the brightness of the shadow area will be adjusted as the final step. In the study by [47], MSR method was applied to enhance the shadow regions for an illuminant independent skin color detection. In addition, MSR was utilized in [48] to detect the vehicle shadow and then eliminate it.

4.2.3. Biomedical applications

Retinex has taken a big part of being used in medical imaging applications [49-53]. In [51] Retinex was applied to be used in automatic analysis correctness of skin lesions. In this regard, MSR was used to enhance the image of the spinal cord for medical purposes. Here, the core of this algorithm is the design of Gaussian surround function. In this regard, image improvement in medical applications mostly consider the spinal cord images. This is because enhancing the details of the spinal cord images lead to an increase in the accuracy of the diagnosis. On the other hand, the author of the study in [52] introduced a real-time image enhancement for gastric endoscopy, by applying the Retinex image enhancement technique on video images. MSRCR had also been employed in [53] to reduce the contrast between arteries and vein increase classification of blood vessels in retinal images. In addition to the three main applications discussed above, Table 1 presents the optimization parameters and applications of Retinex in various fields.

Table 1. Optimization parameters and applications for retinex techniques

Authors	Optimization parameter	Application	SSR	MSR
Md Shukri Asmuni [40]	Require initial estimation of the inner and outer boundaries	Iris detection		√
Zhang and Duan [34]	Weight optimization of Gaussian filters	Standard images		√
Chao, Lai [39]	NA	Medical image segmentation		√
J Li [50]	Image color constancy, local dynamic range compression, color enhancement	Standard images enhancement		√
Lin, Haoning [36]	Gain-offset method for prior-to-display treatment	Nighttime image enhancement		√
Amarjot Singh [35]	Contrast threshold needs to be fixed	Medical image segmentation		√
Byungju Lee, Byung Cheol [54]	NA	HDR image		√
Yonghun Shin, Soowoong Jeong [55]	Gamma and standard deviation for Gaussian kernel filter need to be set manually	Standard image enhancement		√
Zhu Rong, Wang Li Jun [56]	Attenuation coeeficient	Image dehazing	√	
Xia Lan, Huanfeng Shen [13]	The relationship and the fidelity term between the illumination and reflectance is conserned	Satalight images		√
Doo Hyun, Ick Hoon [57]	Relying on gamma factors for their just noticeable difference based nonlinear low pass filter	Standard color image	√	
Guang [58]	Parameter that control frequency decay rate	Standard color image	√	

*NA – not applicabel

4.3. Recommendation for future research

Based on the studies included in this review, some recommendations for future studies of Retnix can be proposed. Firstly, as the review summarized in the previous section, it can be observed although improvements have been made to the original Retinex theory, most algorithms are relying on the optimization parameters. The parameters need to be manually set where the performance of the improved algorithms are highly affected. The selection of the optimum parameter could be biased and not consistent to be used as a standard framework for Retinex enhancement. Therefore, a model to reduce the dependency on the optimization parameter could be developed.

Improvements can also be made on the existing techniques where quantifiable parameter to reflect on the degree of the image degradation can be further investigated. To date, there is no single measurement could represent the degradation level of the image. Here, human conception is mainly utilized to address the aspect of images quality. Hence, future studies could be implemented to explore the degradation level of the image where the level of contrast, illumination, and image details are considered. In this regard, a formulation of the optimum parameter that represents these factors could be proposed in order to define the level of image degradation.

Addition improvements on the existing Retinex theory could be investigated to enhance the overall illumination of the image. Here, the dynamic range compression in the reflectance components can be further pushed. Finally, a unifying framework to modify the reflectance components of Retinex theory will be also beneficial for image enhancement to be applied in various applications, see Table 1.

5. CONCLUSIONS

This paper presents the variation of the Retinex algorithm models for uneven intensity correction. Here, strength and weakness aspects of every implementation theory are highlighted and discussed. Furthermore, the relationship between the illumination and reflectance is addressed. In summary, this paper illustrates the applications and approaches the implementation of the Retinex theory. In addition, a robust framework of modifying the reflectance components of the Retinex could be explored and further improved.

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