Application of Low Illuminance Image Enhancement Based on Improved Retinex Algorithm in Urban Utility Tunnel

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Abstract

In order to optimize the low illumination image processing during the procedure of robot smart inspection in urban utility tunnel, this paper proposes an idea to improve the Retinex algorithm. The existing Retinex algorithms are multi-scale Retinex algorithm and color-recovery multi-scale Retinex algorithm (MSRCR). Compared with these two algorithms, the traditional single-scale Retinex algorithm has the obvious advantage of fast speed, but it also has the issues of more halo and color distortion. One method is showed in this paper to optimize the image enhancement process by using the Butterworth low-pass filter instead of the traditional Gaussian low-pass filter to estimate the values of illuminance image needed in the Retinex algorithm calculation. The result shows that the above problems are solved to some extent. This modified Retinex algorithm is compared with another two algorithms subjectively and objectively in this paper. Several indicators (brightness, standard deviation, average gradient, and information entropy) of the proposed algorithm are superior to the other two algorithms.

Keywords

image enhancement; low illuminance image; Retinex algorithm; Butterworth filter.

1. Introduction

Nowadays, the rapid development of an important infrastructure - urban utility tunnel ensures the function of cities, and it is of great significance to ensure the everyday operation of the pipe galleries and related facilities in them. Therefore, the inspection work is indispensable. The manual inspection will encounter the problem of gaining incomplete and unsystematic information. The inspectors will also be affected and restricted by factors such as skills, experience, and mind [1]. In recent years, the application of robot inspection in the urban utility tunnel has been developed, and the use of robots and image processing and recognition technology has effectively supplemented the inadequacy of manual inspection. The low illumination environment is a common condition in these infrastructures. The Retinex algorithm can well handle issues of low illuminance images enhancement. The traditional single-scale algorithm has many problems such as halo, whitening, color distortion, loss of detail. While the improved algorithm, multi-scale Retinex algorithm, and MSRCR algorithm, solve these problems to a certain extent, but the single-scale algorithm still has obvious advantages in algorithm speed [2]. In this paper, an improved single-scale Retinex algorithm is proposed. Compared with the traditional Retinex algorithm and some other algorithms, it solves the problems of whitening, floodlighting and color distortion when dealing with low and extremely low illuminance images.

2. Traditional Retinex Theory

2.1 Traditional SSR

E.H.Land first proposed the Retinex theory in the 1970s. The theory has two main points: 1) the ability of an object to reflect light at various wavelengths determines the color of the object that people see, regardless of the illuminating light's nature; 2)The color of the object is consistent, and uneven illumination has little effect on its color [3-4]. Based on this theory, the single-scale Retinex (SSR) algorithm [4], the multi-scale Retinex [5] algorithm (MSR), and the color-recovery multi-scale Retinex [6] algorithm (MSRCR) were developed. These algorithms achieve different image enhancement effects in different applications. Retinex theory holds that an image can be divided into two components: the illumination component L(x, y) and the reflection component R(x, y). The formula is expressed as:

$$S(\mathrm{x},\mathrm{y}) = L(\mathrm{x},\mathrm{y}) * R(\mathrm{x},\mathrm{y}) \tag{1}$$

In formula (1), S(x, y) is the original image, L(x, y) is the illumination component, and L(x, y) usually changes slowly, which is a relatively smooth component in the original image and can be considered as a low-frequency signal. R(x, y) is the reflection component, and R(x, y) usually changes fast, reflecting the edge and structure information of the object in the original image, which can be considered as a high-frequency signal. Based on this, the SSR algorithm aims to reduce the influence of the illumination component on the original image as much as possible and directly obtain the reflection component as an enhanced image where definition, contrast and brightness are all improved. Usually, formula (1) is first transferred to the logarithmic domain to facilitate calculation. The SSR algorithm can be expressed as:

$$R_i(\mathrm{x},\mathrm{y}) = \log S_i(\mathrm{x},\mathrm{y}) - \log L_i(\mathrm{x},\mathrm{y}) \tag{2}$$

Where i is the color channel, and Ri(x, y) is the reflection component of the ith channel, which is regarded as the output image; Li(x, y) is the illumination component of the ith channel, which is traditionally estimated by operating the original image with the Gaussian low-pass filter, which is processed as follow:

$$R_i(\mathrm{x},\mathrm{y}) = \log S_i(\mathrm{x},\mathrm{y}) - \log[F(\mathrm{x},\mathrm{y}) * S_i(\mathrm{x},\mathrm{y})] \tag{3}$$

Where * is convolution, F(x,y) is surround function:

$$F(\mathrm{x},\mathrm{y}) = ke^{\frac{-r^2}{\sigma^2}} \tag{4}$$

Where σ is Gaussian constant, which is also the scale of Retinex algorithm rhythm, k can be culculated by:

$$\iint F_i(\mathrm{x},\mathrm{y})dxdy = 1 \tag{5}$$

2.2 Traditional MSR Algorithm

The SSR algorithm cannot meet the practical needs of image details, structure enhancement and color fidelity at the same time, so D.J.Jobson et al. proposed the MSR algorithm [4], which is the linear weighted summation of SSR algorithm. The mathematical expression is:

$$R_{\mathrm{MSR}i}(\mathrm{x},\mathrm{y}) = \sum_{n=1}^{N} W_n \{\log S_i(\mathrm{x},\mathrm{y}) - \log[F(\mathrm{x},\mathrm{y}) * S_i(\mathrm{x},\mathrm{y})]\} \tag{6}$$

Where Wn is the weights of different scale, and $\sum_{n=1}^{N} W_n = 1$.

2.3 MSRCR Algorithm

After processing by the MSR algorithm, the image may have problems of increased noise and color distortion. Therefore, D.J.Jobson further proposed the MSRCR (MSR with color restoration) algorithm [4], the mathematical expression is:

$$R_{\mathrm{MSRCR}i}(\mathrm{x},\mathrm{y}) = C_i(\mathrm{x},\mathrm{y}) R_{\mathrm{MSR}i}(\mathrm{x},\mathrm{y}) \tag{7}$$

Where Ci(x,y) is the color restoration function of the ith channel:

$$C_i(x,y) = \beta\{\log\left[\alpha L_i(x,y)\right] - \log\left[\sum_{j=1}^{3} L_j(x,y)\right]\} \tag{8}$$

Where β is a gain constant and α controlls the nonlinear level. The MSRCR algorithm uses a color restoration function to adjust the proportional relationship between the 3 color channels in the original image, thereby highlighting the information of the relatively dark regions to eliminate image color distortion. The processed image has a higher local contrast, and the brightness is similar to the real scene, and the image will become more vivid.

3. Modified SSR Algorithm

The traditional SSR algorithm using a Gaussian low-pass filter doesn't have an obvious effect in improving the image details. In circumstances of low-illuminance images and even extremely low-illuminance images in urban utility tunnel, the traditional SSR can't perform well. The reason is that in the traditional SSR algorithm, the Gaussian low-pass filter used in the filtering process inevitably loses some high-frequency components, so the image will lose some details and edges, resulting in image distortion. The modified algorithm in this paper will use a Butterworth low-pass filter instead of a Gaussian low-pass filter to smooth the image. The processed image contains more detail and information and has a more uniform illumination effect, which also greatly solves the color distortion problem. The experimental results will be compared with the traditional SSR algorithm and the algorithm of [7] to prove that the Butterworth low-pass filter does have better results.

3.1 The Comparison of low-pass filters

Three low-pass filters are compared in figure 1.

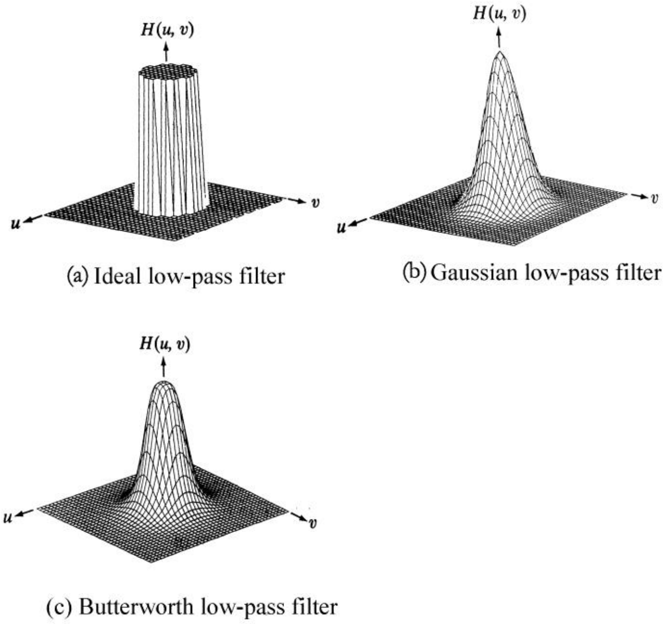


Fig. 1 Comparison of 3 filters

The ideal low-pass filter is very sharp, and its mathematical expression is:

$$H(u,v)=\begin{cases}1, D(u,v)<D_0\\0, D(u,v)\geq D_0\end{cases} \tag{9}$$

The Gaussian low-pass filter is very smooth, and its mathematical expression is:

$$H(u,v)=\exp\left[\frac{-D^2(u,v)}{2D_0^2}\right] \tag{10}$$

While the filtering level of Butterworth is between these two filters, and its mathematical expression is:

$$H(u,v)=\frac{1}{1+\left[\frac{D(u,v)}{D_0}\right]^{2n}} \tag{11}$$

In equation (9), (10), (11), $D(u,v)=\sqrt{u^2+v^2}$; D0 is cut-off frequency; n is the order of Butterworth filter. First order Butterworth filter is used in this paper. The equation (3) can be transferred into:

$$R_i(x,y)=\log S_i(x,y)-\log\left[F_{\mathrm{BW}}(x,y)*S_i(x,y)\right] \tag{12}$$

Where FBW(x,y) is Butterworth operator.

3.2 The Steps of the Modified Algorithm

OpenCV 3.0 in VS 2017 is used in this paper. The processing targets are low and extremely low illuminance images. The steps are shown in fig 2:

1) Read the test image S(x,y).

2) Perform a Laplace transform on Si(x, y), then calculate the result with Butterworth operator. Get FBW(x, y)* Si(x, y).

3) Perform the inverse transformation on FBW(x, y)* Si(x, y) and get illumination opponent Li(x,y).

4) Get the logarithm of Li(x,y) and Si(x,y), and get.

5) Perform a mask operation on the final output image Ri(x, y) to tune its sharpness.

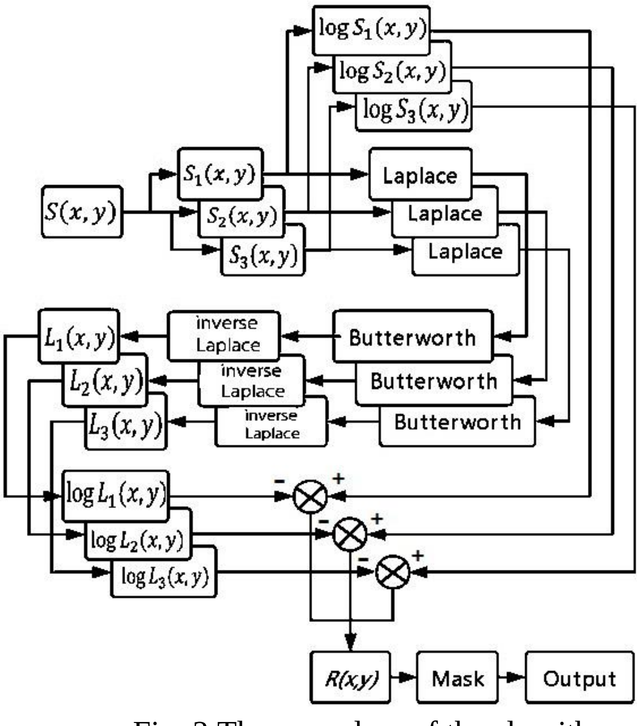


Fig. 2 The procedure of the algorithm

4. Results and analysis

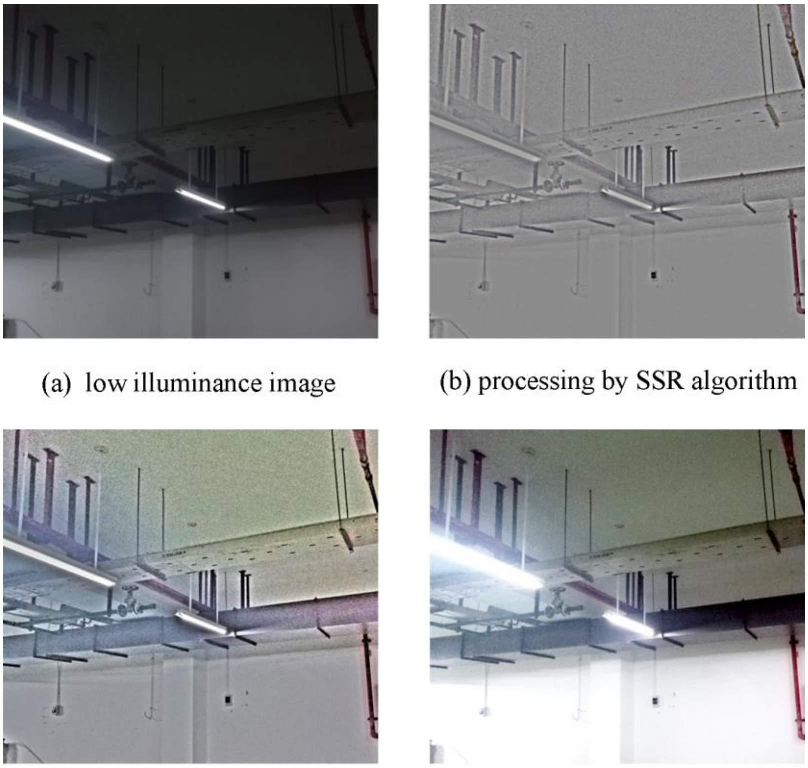
The test images used in the experiment are low and extremely low illuminance images in a pipe gallery. They are photos of the doorway of an underground electrical control room in Shanghai, and the images of a pedestrian passage in a utility tunnel. The test images are both of low illuminance and bad quality. As shown in Figure 3:

(a) Low illuminance image (b) extremely low illuminance image

Fig.3 Test Images

4.1 The comparision of different algorithms

In this paper, three algorithms based on Retinex theory are compared, which are the modified SSR algorithm, the traditional SSR algorithm and the HSV space-based multi-scale color restoration Retinex algorithm in paper [7], as shown in Fig. 4 and Fig. 5.

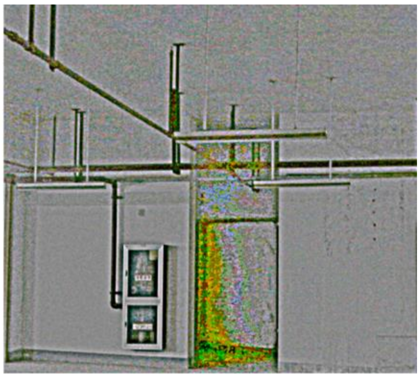


(a) low illuminance image (b) processing by SSR algorithm

(c) processing by algorithm in paper [7] (d) processing by modified SSR

Fig.4 Algorithms comparison of the low illuminance image

(a) extremely low illuminance image



(b) processing by SSR algorithm

(c) processing by algorithm in paper [7]

(d) processing by modified SSR

Fig.5 Algorithms comparison of the extremely low illuminance image

4.2 Subjective evaluation of processing results

It can be concluded that the traditional SSR algorithm is not suitable for color image enhancement for its inability to tackling whitening, halo, and color distortion issues. The test images are processed by MSRCR algorithm based on a transformation from RGB space into HSV space, which is tested in paper [7]. This approach helps a lot with color distortion issues. But when it comes to extremely dark image, whitening issues still exist and color distortion still occurs in the darkest parts of the images. Paper [7] has little advantage in low illuminance image processing compared with this paper. The modified SSR algorithm focuses on how to handle the extremely dark conditions that may occur in urban utility tunnels, which has a more obvious and better result than the traditional one and the paper [7] 's and narrow the whitening and halo problem into a smaller level.

4.3 Objective evaluation of processing results

Standard deviation, average gradient, brightness and information entropy are involved in the objective evaluation. The standard deviation reflects the difference value between the image pixel value and the mean pixel value, which can reflect the regional contrast level to a certain extent. The larger the standard deviation, the better the image quality. Average gradient is a reflection of tiny detail's change rate, which can also be regarded as an indicator of image definition. Brightness characterizes the degree of image shading. In this paper, the brightness is normalized. Brightness = 1 means extremely bright (white), and brightness = 0 means extremely dark (black). The information entropy of the image is to quantify the richness of color with probability. The larger the entropy, the richer the image information and color [2]. The indicators of three algorithms and the test images are shown in Table 1 and Table 2:

Table 1. Parameters comparison of the low illuminance image

Algortithms	Standard deviation	Average gradient	Brightness	Information entropy
Test image	38.6324	2.1863	0.2417	6.5870
Traditional SSR	15.3420	5.0231	0.5385	5.2638
Paper [7]	29.0215	8.7269	0.5786	6.9101
Modified SSR	69.2891	5.0982	0.6247	7.1443

Table 2. Parameters comparison of the extremely low illuminance image

Algortithms	Standard deviation	Average gradient	Brightness	Information entropy
Test image	9.1543	0.9857	0.0593	4.9454
Traditional SSR	32.9052	10.2856	0.5531	6.6254
Paper [7]	30.3529	8.9375	0.6342	7.4196
Modified SSR	74.5770	7.8513	0.5654	7.4999

It can be concluded that the modified SSR has an absolute advantage in standard deviation because of the better contrast in some part of the test images. When it comes to the average gradient, this algorithm has no advantage, which means it has no edge over other algorithm definition wise. But through previous evaluation, it can also be seen that other algorithms cannot handle the color distortion issues even if they can raise the definition. The brightness is not as high as the paper [7], but the color fidelity of this paper is very high, which is of great significance. The information entropy of modified SSR is better than the other two algorithms, which means it has better color and image information, and the visual effect is better.

5. Conclusion

In this paper, the low-illuminance image is enhanced by a modified SSR algorithm using the Butterworth low-pass filter. The results are compared with the traditional SSR algorithm and another Retinex-based algorithm (paper [7] algorithm) and evaluated from subjective and objective angles. It is concluded that the algorithm of this paper works better. This idea of optimizing the Retinex algorithm can be applied to the smart inspection based on image processing in urban utility tunnel and has certain practical significance on some occasions.

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