Improved dark channel prior image dehazing algorithm based on wavelength compensation

Zhixiang Chen\textsuperscript{1,2}, Binna Ou\textsuperscript{1,2}, Qianyi Tian\textsuperscript{1,2}

\textsuperscript{1}Key Laboratory of Data Science and Intelligence Application, Fujian Province University, Fujian Zhangzhou, China
\textsuperscript{2}College of computer, Minnan Normal University, Fujian Zhangzhou, China

* Corresponding author: zxchenphd@163.com

Abstract. For the dark channel prior image dehazing algorithm to defog the foggy image with the same transmittance, the recovery result will have a more serious color shift problem. An image defogging algorithm based on different color wavelength compensation is proposed. Firstly, the median dark channel map is obtained by the median filtering method, and then the optical attenuation coefficients of different wavelengths are calculated to obtain the transmittance of Red-Green-Blue (RGB) three channels. Finally, the revised parameters are substituted into the atmospheric scattering model to restore the fog-free image. The experimental results show that the foggy image containing bright areas such as the sky have a good processing effect, which significantly reduces the color distortion of the bright area, and the image is clearer and more natural.

1. Introduction

In fog and haze weather, due to the absorption or scattering of atmospheric light by the suspended particles in the atmosphere, the collected outdoor images are degraded, the visibility and contrast of the scene are reduced, the color is distorted, and many scene features are difficult to identify [1]. This will affect the image acquisition and processing system, and even affect the normal operation of systems such as maritime monitoring, road monitoring, satellite remote sensing and target recognition, which will cause inconvenience to people's production and life. Therefore, it is of great practical value to defog the image in foggy weather to ensure the stability of the visual system performance.

There are two main types of image defogging methods: one is image enhancement method, the other is image restoration method. A single image dehazing technique based on dark channel prior is an image restoration method proposed by He Kaiming et al. [1]. This method can get good defogging effect for most outdoor images, but for bright areas such as sky or white objects where dark channel prior is not established, researchers have made many improvements. Liu et al. assumed that haze had the same effect on the local area of the image, fused the estimated two initial transmission graphs to get more accurate transmission graphs [2]. Xie et al. proposed a fast kernel regression model, which combined wavelet decomposition to achieve image defogging[3]. In this paper, an image defogging algorithm based on light wavelength compensation is proposed on the basis of dark channel color priori. Based on the attenuation corresponding to each light wavelength, the attenuation difference on the propagation path is compensated, and the color change compensation is carried out to restore the color balance, and then the fog-free image is restored.
2. Dark channel prior theory

2.1 Atmospheric scattering model
In foggy weather, before reaching the camera, light attenuates through absorption, scattering and refraction of these particles, which degrades the outdoor scenery image. The atmospheric scattering model [4,5] is used to describe the process.

\[ I(x) = t(x) \cdot J(x) + (1 - t(x)) \cdot A \]  

(1)

In (1), \( x \) represents the coordinates of the pixels. \( I(x) \) denotes the input foggy image, \( J(x) \) denotes the restored fog-free image, \( t(x) \) denotes the transmittance of light from a scene, \( A \) denotes atmospheric light value. The defogging based on this model is to restore the original fog-free image \( J(x) \) from the observed image \( I(x) \), the known quantity is only \( I(x) \). To obtain \( J(x) \), the transmittance \( t(x) \) and atmospheric light value \( A \) are required.

2.2 Dark channel prior
There are always pixels with low brightness and close to 0 in the non-sky part of most outdoor fog-free images. For image \( J \), dark channel is expressed as:

\[ J_{\text{dark}}(x) = \min_{c=\{R,G,B\}} \left( \min_{y \in \Omega(x)} J_c(y) \right) \approx 0 \]

(2)

In (2), \( J_{\text{dark}} \) represents the dark channel color of the outdoor fog-free image, \( c \) represents the three channels of red, green and blue, \( J_c(y) \) represents the image of the \( c \) channel of the restored clear image, and \( \Omega(x) \) represents the local area centered on \( x \) pixels.

2.3 Through the dark channel prior dehaze
Assuming that the atmospheric light value \( A \) is given, in the local region \( \Omega(x) \), \( A \) is uniform and the transmittance \( t(x) \) is fixed. The minimum value of formula (1) is calculated as follows:

\[ \min_{y \in \Omega(x)} J_c(y) = t(x) \cdot \min_{y \in \Omega(x)} J_c(y) + (1 - t(x)) \cdot A \]  

(3)

The minimum operation is performed independently in three color channels, the minimum values of the three color channels are calculated, the expression of the dark channel of foggy image I can be obtained as follows:

\[ \min_{c=\{R,G,B\}} \left( \min_{y \in \Omega(x)} J_c(y) \right) = t(x) \cdot \min_{c=\{R,G,B\}} \left( \min_{y \in \Omega(x)} J_c(y) \right) + (1 - t(x)) \cdot A \]  

(4)

Combining with the dark channel priori theory, \( J_{\text{dark}} = 0 \), and in order to maintain the subjective visual effect of the processed fog-free image, the coefficient \( \omega(0<\omega\leq1) \) is introduced. The value depends on the actual situation, usually 0.90–0.97. And sorted out as follows:

\[ t(x) = 1 - \omega \min_{c=\{R,G,B\}} \left( \min_{y \in \Omega(x)} J_c(y) / A \right) \]  

(5)

The first 0.1% pixels in the dark channel color image of foggy image are taken and the corresponding positions of the pixels in the original image are found. The maximum brightness of these pixels is taken as the atmospheric light value \( A_c \). By substituting the calculated transmittance \( t(x) \) and atmospheric light value \( A \) into the formula (1), the fog-free image \( J(x) \) is obtained.

\[ J(x) = \frac{I(x) - A_c}{t(x)} + A \]  

(6)

3. Algorithms in this paper
The dark channel prior fog removal algorithm does not satisfy the assumption of bright areas such as sky and white clouds, and the restoration results will show obvious color distortion. For other areas, using the same transmittance to process RGB three channels will also cause insufficient or excessive
restoration, which will affect the visual effect of the image. The bright areas of foggy images are generally white, and the brightness values of the three color channels are similar [6]:

$$\Delta_c = I_c - A_c, c \in \{R, G, B\}$$  \hspace{1cm} (7)

$$\Delta_k \approx \Delta_G \approx \Delta_B$$  \hspace{1cm} (8)

$\Delta_c$ is the relative color value. Because the transmission rate of dark channel prior estimation is relatively small, the brightness value difference of the three channels, even if small, will be rapidly amplified after being divided by a small one, resulting in a large color difference between the restored image and the original image. To solve this problem, an improved method is proposed to make the obtained transmission rate more close to the real one. Considering the different attenuation of light of different wavelengths, corresponding light compensation is carried out, that is, light of different wavelengths has different transmittance, which cannot be regarded as the same $t$. Taking RGB color channel as an example, the different transmittance of RGB three-channel can be calculated.

$$t_R \neq t_G \neq t_B$$  \hspace{1cm} (9)

### 3.1 Median dark channel prior

When the dark channel prior algorithm is applied to the image with sky area, the result of haze removal is easy to Halo effect and the image edge details are blurred. For this reason, the median filter is adopted to modify the dark channel prior, and the modified median dark channel $J_0^{\text{dark}}$ [7] is:

$$J_{0, \text{dark}}(x) = \text{med} \left( \min_{y \in \Omega(x), c \in \{R, G, B\}} (J^c(y)) \right)$$  \hspace{1cm} (10)

$\Omega(x)=3*3$ window size. Use formula (10) to calculate the median dark channel, as shown in Fig1(b). By comparing the dark channel prior diagram in Fig. 1(c), it is found that the median dark channel eliminates the helo effect and the image edge details are clear.

(a) foggy image  (b) median dark channel  (c) dark channel prior  

Fig.1. Comparison of median dark channel and dark channel

### 3.2 Improvement of transmittance

According to Lambert-Bouger law, the relation between incident ray intensity $I(v)$ and transmitted ray intensity $I_0(v)$ after transmission distance $d$ is expressed as:

$$I_0 = I(v)e^{-\mu d}$$  \hspace{1cm} (11)

$\mu$ is the attenuation coefficient. Transmittance is defined as:

$$t = \frac{I_0(v)}{I(v)}$$  \hspace{1cm} (12)

From formulas (11) and (12), the relationship between transmittance $t$, attenuation coefficient $\mu$ and transmission distance $d$ is obtained as follows:

$$t = e^{-\mu d}$$  \hspace{1cm} (13)

Kruse [8] proposes that the relationship between the attenuation coefficient and visibility of light with different wavelengths propagating in fog is expressed by the following formula:

$$\mu = \frac{3.912}{V} \left( \frac{0.55}{\lambda} \right) (\text{km}^{-1})$$  \hspace{1cm} (14)
V is atmospheric visibility, \( \lambda \) is the wavelength of light, q is the wavelength correction factor. According to experimental observations and theoretical calculations, Kim et al. [9] proposed that the wavelength correction factor q is determined by the following formula:

\[
q = \begin{cases} 
0 & , \ V < 500m \\
V - 0.5 & , \ 500 \leq V < 1km \\
0.16V + 0.34 & , \ 1km \leq V < 6km
\end{cases}
\]  

(15)

When the visibility is around 200m, the visibility model has a large error, and the image restoration effect is of little significance. This paper mainly studies the common conditions of visibility greater than 500m. According to formula (13) and (14), the transmission rate of light with wavelength \( \lambda \) when the visibility is V and the propagation distance is d is t:

\[
t_j(x) = e^{-\mu(\lambda) d(x)}
\]  

(16)

The transmission rate of light t is also called the residual energy ratio of light [10], which represents the ratio of the initial energy \( E_0^{\text{initial}}(x) \) of a beam of light to the residual energy \( E_0^{\text{residual}}(x) \) after a distance of d(x). It is expressed as follows:

\[
t_j(x) = \frac{E_0^{\text{initial}}(x)}{E_0^{\text{residual}}(x)} = 10^{-\mu(\lambda)d(x)} = Nrer(\lambda)^{g(x)}
\]  

(17)

\( \mu(\lambda) \) represents the attenuation coefficient of light whose wavelength is \( \lambda \), and \( Nrer(\lambda) \) represents the standard residual energy ratio. In this paper, the standard unit is 100 meters. According to equations (16) and (17), we can get:

\[
Nrer(\lambda) = e^{-\frac{V}{100}}
\]  

(18)

The standard residual energy ratio of light of different wavelengths after the propagation distance of d(x) is different. For the bright region in the image, the brightness values of the three color channels are relatively high and the differences are small. When \( \lambda_R = 625nm, \lambda_G = 514nm, \lambda_B = 459nm \), in different visibility, the standard residual energy of the three color channels is shown in table 1 after each 100m attenuation. It can be seen that in common visibility, the \( Nrer(\lambda) \) values of the three channels are deviated to a large extent. Blue light has the fastest attenuation speed, green light has the second fastest, and red light has the slowest. The farther the propagation distance is, the more obvious the deviation of the three channels \( Nrer(\lambda) \) is. Therefore, it is necessary to process images with different transmittance for the three channels of RGB.

| V/km | 0.6 | 0.7 | 0.8 | 0.9 | 1   | 2   | 4   | 6   |
|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Nrer(R) | 0.5262 | 0.5819 | 0.6243 | 0.6631 | 0.6903 | 0.8351 | 0.9139 | 0.9417 |
| Nrer(G) | 0.5209 | 0.5703 | 0.6058 | 0.6370 | 0.6698 | 0.8186 | 0.9048 | 0.9324 |
| Nrer(B) | 0.5157 | 0.5590 | 0.5937 | 0.6243 | 0.6499 | 0.8023 | 0.8859 | 0.9321 |

For the foggy image in Fig.1 (a), the RGB three-channel components are taken respectively, and the transmittance maps and histograms of the three channels are obtained respectively by using the dark channel prior theory. The results are shown in Fig.2. For the transmittance of each pixel in the image, the dark channel priori algorithm only obtains the same transmittance value in the RGB three channels. From Fig. 2, it can be seen that the transmittance of the three channels is obviously different. Simply substituting the transmittance of the three channels with the same value may lead to larger errors in the restoration results. According to the different attenuation of light at different wavelengths, the transmittance of three RGB channels is compensated by corresponding wavelength. The compensated transmittance and histogram of three RGB channels are obtained as shown in Fig. 3. It can be seen that the compensated three-channel transmittance is closer.
4. experimental results and analysis

Three channels with different transmittance are used and formula (6) is substituted to obtain the three-channel defogging image, and then the three-channel defogging image is synthesized into the final defogging image. The experimental results are shown in Fig. 4.

4.1 Subjective comparison

In order to evaluate the effectiveness of the algorithm and detect the quality of the image processed by the algorithm, the image restoration effect of the algorithm is compared with that of the dark primary color algorithm, the guided filter algorithm [11] and the Taral algorithm [12]. The comparison results are shown in Fig. 5. From Fig. 5 (b), it can be seen that the results of dark channel algorithm for fog removal are not good for sky region restoration, and the color offset is serious. From Fig. 5(c), it can be seen that Taral algorithm has weak fog removal effect, the processed image still has fog residue, Halo effect appears on the edge of the building and the overall contrast is not high, and the overall image appears color distortion. From the comparison of Fig. 5(d) and Fig. 5(e), it can be seen that the processing results of the guided filtering algorithm show color offset and distortion in the sky and white buildings, and the color of the white areas is yellow. The algorithm proposed in this paper has a
good processing effect on the image containing the sky area, and the color restoration effect is good. The visual color of the original image is well maintained in the white area. The color of the white object is undistorted, the sky area is bright and the stereo sense is stronger. This is due to the correction of the transmittance and atmospheric light value.

![Image showing comparison of defogging results]

(a) foggy image (b) dark channel (c) Taral (d) guided filtering (e) ours

Fig. 5. Comparison of defogging results

4.2 Objective comparison
In order to objectively evaluate the defogging effect of several algorithms, the image in Fig. 5 is selected to evaluate the image quality of different algorithms from the indexes of peak signal-to-noise ratio (PSNR), information entropy (IE), effective detail intensity ratio (EDIR), histogram similarity (HS) and structure similarity (SS). The larger the values of these indexes, the better the image quality is. From the objective evaluation data in Table 2, it can be seen that the signal-to-noise ratio and information entropy of the algorithm are higher, which shows that the image quality of the algorithm is better after fog removal. Effective detail intensity ratio, histogram similarity and structure similarity are also better than the other three algorithms, which shows that the matching degree between the algorithm and the original image features is higher, and the ability to maintain the original image structure information is stronger.

| Foggy image | Defogging algorithm | PSNR | IE  | EDIR | HS   | SS   |
|-------------|---------------------|------|-----|------|------|------|
| **Image 1** |                     |      |     |      |      |      |
|             | Dark Channel        | 10.779 | 6.804 | 0.293 | 0.602 | 0.600 |
|             | Guided filtering    | 13.647 | 7.094 | 0.305 | 0.823 | 0.837 |
|             | Taral               | 9.919  | 6.925 | 0.309 | 0.476 | 0.470 |
|             | ours                | 13.894 | 7.089 | 0.307 | 0.844 | 0.850 |
| **Image 2** |                     |      |     |      |      |      |
|             | Dark Channel        | 9.792  | 6.904 | 0.186 | 0.783 | 0.783 |
|             | Guided filtering    | 13.535 | 7.312 | 0.198 | 0.929 | 0.943 |
|             | Taral               | 12.985 | 7.249 | 0.174 | 0.441 | 0.056 |
|             | ours                | 14.023 | 7.084 | 0.2022 | 0.965 | 0.964 |
| **Image 3** |                     |      |     |      |      |      |
|             | Dark Channel        | 11.919 | 6.479 | 0.278 | 0.790 | 0.823 |
|             | Guided filtering    | 14.213 | 6.657 | 0.277 | 0.912 | 0.905 |
|             | Taral               | 13.847 | 7.057 | 0.329 | 0.813 | 0.8475 |
|             | ours                | 14.896 | 7.011 | 0.305 | 0.899 | 0.904 |

5. Conclusion
Based on the dark channel prior assumption and atmospheric scattering model, a single image defogging algorithm using wavelength compensation is proposed in this paper. The Halo effect of the image is eliminated by median filtering, and the transmittance and atmospheric light value are optimized by the attenuation characteristics of different wavelengths, thus the color offset of the image is corrected. The restored image has high overall brightness, rich details and good visual effect.
Acknowledgments
This work was supported by the Natural Science Funds of China(No.61701213) and the Scientific and education Research Project Funds of Fujian Province(JAT160283, JK2016025)

References
[1] K. M. He, S. Jian, X. Tang,{IEEE} Trans. Pattern Anal. Machine Intell. 33(12):2341-2353(2004).
[2] H. B. Liu, J. Yang,Z. P. Wu ,et al, Journal of Electronic Imaging, 24( 1) : #013020(2015).
[3] C. H. Xie,W. W. Qiao, X. X. Zhang,et al, Journal of Electronic Imaging, 25( 4 ) :#043003(2016).
[4] S. G. Narasimhan,S. K. Nayar, Int J Comput Vision, 48(3):233-254(2002).
[5] R. T. Tan, Proceeding of IEEE conference on Computer Vision and Pattern Recognition,1-8(2008).
[6] J. G. Jang, T. F. Hou, M. B. Qi, Journal of Circuits and Systems, 16( 2) : 155-160(2011).
[7] K. B. Gibson, D. T. Vo, T. Q. Nguyen, {IEEE} Trans. Image Processing, 21(2): 662-673(2012).
[8] Paul W. Kruse. Transmission and Detection. Wiley, New York(1962).
[9] I.I. Kim, B. McArthur, E. J. Korevaar. Optical Wireless Communications III, Proc. SPIE, 4214:26-37(2001).
[10] J. T. Houghton, The Physics of Atmospheres, 2nd ed. Cambridge, UK.: Cambridge Univ. Press, 2001, ch.2.
[11] K. M. He, S. Jian, X. Tang, {IEEE} Trans. Pattern Anal. Machine Intell, 35( 6) : 1397 – 1409(2013).
[12] J. P. TAREL, R. E. NHAUTI. Proceedings of the 2009 IEEE 12th International Conference on Computer Vision. Japan, 2201 – 2208 (2009).