Polarimetric dehazing utilizing spatial frequency segregation of images

FEI LIU,1 LEI CAO,1 XIAOPENG SHAO,1,* PINGLI HAN,1 AND XIANGLI BIN1,2

1School of Physics and Optoelectronic Engineering, Xidian University, Xi’an 710071, China
2Academy of Opto-Electronics, Chinese Academy of Sciences, Beijing 100094, China
*Corresponding author: xpshao@xidian.edu.cn

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A procedure for the detection and removal of haze from dense hazy images has been proposed. It involves the analysis on the content of low-spatial-frequency information of a scene. The image contaminated by haze is decomposed into different spatial frequency layers by the wavelet transform, by which the hazy parts of the image are focused on the low-frequency components. A dehazing method combining both the airlight and direct transmission is employed to specially dehaze the low-frequency parts. The high-frequency parts are processed by a transfer function to enhance the clarity of the hazy image. Finally, a dehazed image with high clarity is obtained by image construction which employs the low- and high-frequency components. Experiments and analyses demonstrate the good performance of the scheme in terms of improving the contrast and clarity of hazy images. Particularly, it works well in improving the visual range of images captured in hazy weather conditions.

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1. INTRODUCTION

Over the past decades, haze is more frequently observed as a result of air pollution [1]. Haze reduces image visibility [2], due to unwanted light scatter from particles into the imaging light path, and therefore brings safety hazards to vehicles, aircraft, ships, and even remote sensing. This kind of image degradation is significant when viewing over long horizontal distances, particularly in urban areas. To solve these problems, there has been increasing interest in addressing images acquired in poor-visibility conditions due to haze, with the major objective of enhancing the clarity these images.

Some image enhancement methods proposed in the past require prior information about the imaged scene (e.g., distances) [3,4]. Computer vision methods restore clear-day visibility of an imaged scene relying only on the acquired images but require a change in weather conditions between image acquisitions [5,6]. For example, if an image of haze without the scene of interest can be collected, this image can be subtracted from one which includes the scene of interest and background. This process, however, takes too long to make dehazing of the image practical. Other methods, including dark channel prior way [7], homomorphic filtering [8], and retinex [9], have also been developed.

Since scatter and haze are predominantly linearly polarized, the above-mentioned methods enhance the quality of hazy images but induce an inevitable loss of information. As an alternative, methods utilizing polarimetric information have also been developed to dehaze images [10,11]. In 2001, Schechner et al. were the first to demonstrate that the quality of images taken in poor-visibility conditions could be improved by employing polarimetric imaging [11]. Further studies have been done to improve and perfect their theory in the subsequent years [12]. Mudge and Virgen [13] attempted real-time polarization dehazing with their customized polarimetric camera but did not make any improvement to the dehazing algorithms and only used the dehazing algorithm from Schechner et al. Nishino et al. compared the results of methods with and without polarimetric information and reached the conclusion that dehazing results could be obtained better when using polarimetric information [14].

Although various studies have proved that polarization-based methods are effective in dehazing, the methods neglect that objects and haze differ in spatial frequency distribution in hazy images. The spatial variation of haze contains lower spatial frequencies, because of propagation through atmospheric disturbance, than that of land cover which changes mainly at higher frequencies [15]. As a consequence, the low- and high-spatial-frequency components reflect effects of haze and land cover, respectively, and can be used in dehazing.
In this study, a polarization dehazing method is presented that separately processes the low- and high-spatial-frequency components of the image. Because the low-spatial-frequency components contain more information about the haze, these are first processed with a polarization-based dehazing algorithm. After processing of the low-spatial-frequency components, the high-spatial-frequency components are manipulated with a nonlinear transform. Finally, the two types of components are recombined to achieve reconstruction of high-clarity dehazed images.

2. THEORETICAL BACKGROUND AND METHOD

Studies have shown that haze in images is mainly generated by atmospheric scattering, including by dust, smoke, and water droplets. Mie scattering theory is commonly used to model scattering, describing wavelength-dependent scattering effects. For instance, shorter wavelengths result in detectable haze in environmental conditions where many particles are present, as compared to that in common conditions where haze will only be detected for longer wavelengths of light.

Hazy images present only fuzzy outlines of objects in the imaged scene. As shown in Fig. 1, light from an object is attenuated due to scattering in the propagation path to a polarimetric camera, and the light component that finally arrives at the camera is the direct transmission. Both the effects of the airlight, the scattered ambient light that reaches the camera, and of the scattering of the radiances from the imaged scene increase with increasing distance between the scene and camera. Because haze remains similar in appearance over long distances, the haze spatial distribution is steadier than that of objects in the imaged scene. Based on the aforementioned facts, hazy images can be assumed to have haze dominant in the low-spatial-frequency components of the image, while the high-spatial-frequency components in the image primarily denote the objects in the imaged scene. This spatial frequency segregation enables the decomposition of hazy images into different frequencies to extract the low-spatial-frequency components dominated by haze to generate a clear dehazed image [15].

In conjunction with the frequency decomposition of hazy images, the development of a dehazing algorithm is needed to address the low-spatial-frequency components.

Generally, the image radiance \( I_{\text{total}} \) received by the camera could be expressed as

\[
I_{\text{total}} = D + A,
\]

where \( D \) represents the direct transmission of radiance from the imaged scene and \( A \) denotes the airlight which is light of the illumination sources (e.g., the sun) scattered by atmosphere. The transmission \( D \) is an attenuated fraction of the object radiance. \( I_{\text{object}} \) is a function of the horizontal distance \( z \), expressed as

\[
D = I_{\text{object}} e^{-\beta z},
\]

with \( e^{-\beta z} \) as the transmittance of light, where \( \beta \) is the scattering coefficient. The airlight \( A \) also varies with the horizontal distance \( z \) according to

\[
A = A_\infty [1 - t(z)],
\]

where \( A_\infty \) is the airlight radiance corresponding to an object at an infinite distance. Equations (1)–(3) are the fundamental formulas needed for dehazing employing polarization.

The dehazed images presented by Schechner et al. are represented as the object radiance calculated by

\[
I_{\text{object}} = \frac{I_{\text{total}} - A}{t(z)}.
\]

The numerator of Eq. (4) removes the effect of the airlight by subtraction, and the denominator of Eq. (4) undoes absorption or scattering of light emanating from the object by division by \( e^{\beta z} \). To calculate the airlight, two polarization images \( I_\parallel \) and \( I_\perp \) are searched and can be calculated by Eq. (6), known as the worst and best states of the polarizer, respectively [11]. In the best state, the image irradiance is the closest to the irradiance corresponding to the direct transmission; while in the worst state, the airlight is enhanced relative to the direct transmission [11]. Schechner et al. assumed that only airlight is polarized and this assumption works well in most cases. However, both the airlight and the object’s radiance contribute to the polarization information of the images. Therefore, a dehazing method addressing both parts is chosen for the current work [16].

By employing Stokes theory, the first element \( S_0 \) in the Stokes vector represents the total radiance received by the sensor [17]. So that Eq. (1) could be expressed as

\[
S_0 = S_0^D + S_0^A.
\]

With the Stokes vector, the degree of linear polarization (DoLP) of the image could be easily calculated [16]. Then we employ the Stokes vector and DoLP (for brevity, take \( P \) to represent the DoLP in the subsequent equations) to synthesize the best and worst images [16], shown by Eq. (6) as

\[
I_\parallel = \frac{(1 + P)S_0}{2}, \quad I_\perp = \frac{(1 - P)S_0}{2}.
\]

To make full use of the frequency segregation in the hazy image, one-layer wavelet decomposition is done to both \( I_\parallel \) and \( I_\perp \) utilizing the wavelet transform. Since human eyes are sensitive to the phase distortion of images, bior2.4 wavelet basis which has the linear phase is employed. The images are separated into
high- and low-frequency components. The hazy parts of the image are concentrated in the low-frequency components, and these parts can be dehazed with the following dehazing algorithm.

The DoLP of the image could be calculated by a so-called polarized-difference image, expressed as

\[ P = \frac{\Delta I}{S_0}, \quad (7) \]

where \( \Delta I = I^\parallel - I^\perp \) is the polarized-difference image. As the difference of the worst and best polarization images, \( \Delta I \) is estimated in the following way:

\[ \Delta I = I^\parallel - I^\perp. \quad (8) \]

Similar to Eq. (7), the DoLP of the direct transmission \( (P_D) \) and airlight \( (P_A) \) can be defined as

\[ P_D = \frac{\Delta D}{S_0}, \quad P_A = \frac{\Delta A}{S_0}. \quad (9) \]

It follows then that the expression of a hazy image with polarization can be written from Eq. (10) as

\[ P_S = P_D S_0^P + P_A S_0^A. \quad (10) \]

Combining Eqs. (3)–(5), (7), and (10), the low-frequency components of the hazy image can be dehazed into the actual object radiance by the following form:

\[ L_{\text{object}} = \frac{\Delta I - P_A S_0}{P_D (1 - S_0/A_\infty) + \Delta I/A_\infty - P_A}. \quad (11) \]

Before completing the dehazing of images, the following parameters should be estimated: \( \Delta I, A_\infty, P_A, \) and \( P_D \).

With regard to \( A_\infty \) and \( P_A \), we assume a homogeneous distribution of scattering particles in the atmosphere, so \( A_\infty \) and \( P_A \) remain constant in the image. Their values can be estimated using the region in the image that represents the sky, where \( \Omega \) specifically represents the number of pixels in the sky region of the image [18]. The final estimation of \( A_\infty \) and \( P_A \) can be written as

\[
A_{\infty} = \frac{1}{\Omega} \sum_{(x,y) \in \Omega} \left[ I_{\parallel}^0(x,y) - I_{\perp}^0(x,y) \right], \\
P_A = \frac{1}{\Omega} \sum_{(x,y) \in \Omega} \left[ \frac{I_{\parallel}^0(x,y) - I_{\perp}^0(x,y)}{S_0} \right]. \quad (12)
\]

The DoLP of the direct transmission \( P_D \) is obtained by solving the following differential equation:

\[ d\Gamma^2(P_D)/dP_D = 0, \quad (13) \]

where

\[
\Gamma(P_D) = \text{Cov}(t, L^{-1}_{\text{object}}) = \frac{\text{Cov}\{P_D S_0 - \Delta I, \frac{P_D S_0 - \Delta I - A_\infty (P_D - P_A)}{\Delta I - P_A S_0}\}}{A_\infty^2 (P_D - P_A)}. \quad (14)
\]

The high-frequency parts of the decomposed hazy image represent the details in the hazy image. After the wavelet decomposition, the absolute values of wavelet coefficients become larger, which results in less clarity of certain high-frequency regions in the dehazed image, which can lead to problems in image dehazing. To avoid this consequence, a dual-threshold enhancement algorithm is taken to adjust the high-frequency coefficients, as shown in Eq. (15), such that coefficients within a certain threshold are removed and those outside the threshold are enhanced.

\[
W_{\text{out}} = \begin{cases} 
W_{\text{in}} + (T_2 \cdot (G - 1)) - (T_1 \cdot G), & W_{\text{in}} > T_2, \\
G \cdot (W_{\text{in}} - T_1), & T_1 < W_{\text{in}} \leq T_2, \\
T_1, & T_1 \leq W_{\text{in}} < T_2, \\
-W_{\text{in}} - (T_2 \cdot (G - 1)) + (T_1 \cdot G), & W_{\text{in}} < -T_2,
\end{cases} \quad (15)
\]

where \( W_{\text{in}} \) and \( W_{\text{out}} \) are the wavelet coefficients before and after enhancement transfer, \( G \) is the gain, \( T_1 \) and \( T_2 \) are two thresholds with \( T_1 < T_2 \), and \( T_1 \) is determined by the image size \( n \) and the variance of the image \( \sigma \) by the expression of

\[ T_1 = \sigma \sqrt{2 \log n} / \sqrt{n}. \quad (16) \]

The high-frequency coefficients transferred by the function shown in Eq. (15) will be adjusted by an appropriate gain to lead to an improved high-clarity reconstructed dehazed image utilizing both the dehazed low-frequency components and the adjusted high-frequency components.

For clarity, the detailed processes in our study are summarized in the list below.

**STEP 1:** Synthetic polarized images \( I^\parallel \) and \( I^\perp \).

First, take three origin polarized images \( I(0^\circ), I(45^\circ) \), and \( I(90^\circ) \) by rotating the polarizer to the angles of \( 0^\circ, 45^\circ, \) and \( 90^\circ \). Then, compute the intensity image \( S_0 \) and the DoLP of the image. Finally, produce the synthetic polarized images \( I^\parallel \) and \( I^\perp \) by Eq. (6).

**STEP 2:** Decompose images \( I^\parallel \) and \( I^\perp \).

Employ bior2.4 wavelet basis to conduct one-layer wavelet decomposition of \( I^\parallel \) and \( I^\perp \). Then, obtain the results of low-frequency images \( I_{\text{low}}^\parallel \) and \( I_{\text{low}}^\perp \).

**STEP 3:** Dehaze the low-frequency images \( I_{\text{low}}^\parallel \) and \( I_{\text{low}}^\perp \).

First, extract the sky region of the low-frequency intensity image \( S_{0}^{\text{low}} \) using an automatic algorithm on the basis of brightness, variance, and color measurement of the image. Relying on the extracted sky region, compute the difference image \( \Delta I_{\text{low}} \), the DoLP of airlight \( \rho_{A}^{\text{low}} \), and the DoLP of the direct transmission \( \rho_{D}^{\text{low}} \) of the low-frequency image. Then, estimate the haze-free low-frequency image \( I_{\text{object}}^{\text{low}} \).

**STEP 4:** Compensate the high-frequency components.

Adjust the high-frequency coefficients by Eq. (15).

**STEP 5:** Fuse the dehazed low-frequency image and the compensated high-frequency components by inverse wavelet reconstruction.

**3. EXPERIMENTS AND DISCUSSION**

We captured images of the buildings near the north gate at the roof of the West Building of Xidian University in Xi’an, Shaanxi Province, China using a SONY F717 camera which was mounted by a rotating polarizer. These experiments
were conducted under the conditions of dense haze and poor visibility.

A hazy image is shown in Fig. 2(a). Figure 2(b) shows the dehazed image generated by the proposed dehazing method. The dehazed image clearly exhibits a significant improvement in the contrast and color of the raw image, especially at the region outlined by the red rectangles in the images. The enlarged image sections shown in Figs. 2(c) and 2(d) make this improvement more apparent where buildings not visible in the raw image become clearly visible in the dehazed image. Note that with the dense haze, the raw image in Fig. 2(a) is very fuzzy and the farthest object that can be detected is at about 400 m away from the camera. In the dehazed image Fig. 2(b), the building outlined by a green rectangle that become clear, but was not visible in the raw image, is over 1 km away from the camera. Furthermore, the colors of the distant blocks and the Chinese characters on the top of one building (near the left edge of the red rectangle) are also reconstructed to be clearer in the dehazed image. The edges of the objects in the dehazed image are also well preserved and the details of objects close to the observer are clearer. In combination with the data in Table 1, there is a more distinct demonstration of the improvement. For example, the mean gradient was increased by 3.30 times after dehazing by the proposed method, indicating a great improvement in edge definition. The contrast was increased by 4.24 times, and the improvement was very obvious in the dehazed image. Although our results in Table 1 have no considerable improvement in comparison with results of Schechner’s algorithm, the visual discrepancy between two images is noticeable.

To get more quantitative data on the image improvement from the dehazing, we changed the RGB images into gray images and employed histograms to present the improvement in a wider distribution of pixels over more gray levels, as shown in Fig. 3. The histogram of the dehazed image in Fig. 3(b) shows that there is a much broader span of gray level than that in Fig. 3(a) of the raw image, implying that more details are discerned in Fig. 2(b). Quantification of the improved clarity after dehazing is shown in Fig. 4, where the intensity value versus the horizontal position of the gray images is plotted from a horizontal line that passes through the vertical position of pixel 200. This horizontal line passes through the most noticeable buildings in the hazy image and sky in the hazy and dehazed images. This provides a forceful demonstration of the improvement for the dehazed image which has larger variations in intensity. This distinct difference between the data shows great increase in contrast. The intensity bump in Fig. 4 at

![Fig. 2. Images of the first scene. (a) Raw image depicting the hazy image of the first scene. (b) Dehazed result of the first scene using the presented algorithm. (c) Magnified region on the red rectangle in (a). (d) Magnified region on the red rectangle in (b).](image)

![Fig. 3. Histograms of the hazy image in Fig. 2(a) (left) and the dehazed image in Fig. 2(b) (right).](image)

<table>
<thead>
<tr>
<th></th>
<th>Hazy Image</th>
<th>Schechner’s</th>
<th>MSR</th>
<th>Dehazed Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean gradient</td>
<td>1.7880</td>
<td>5.8149</td>
<td>5.7770</td>
<td>5.8964</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.1834</td>
<td>0.2892</td>
<td>0.1002</td>
<td>0.3253</td>
</tr>
<tr>
<td>Contrast</td>
<td>0.0906</td>
<td>0.3557</td>
<td>0.2877</td>
<td>0.3840</td>
</tr>
</tbody>
</table>
horizontal position pixel from 300 to 360, which represents the white building in the middle of the image, provides a good example. Compared with the hazy image, there is nearly a factor of two improvement in the relative contrast in the dehazed image.

Further analyses were conducted on the comparison of three dehazing methods on their dehazing effects. Results are displayed in Fig. 5, in which Fig. 5(a) is the hazy image, Fig. 5(b) is the dehazed image by employing Schechner’s algorithm without any additional image processing, Fig. 5(c) is the dehazed image using the multi-scale retinex (MSR) algorithm, and Fig. 5(d) is the result processed by the proposed method in this study. Serious color distortions appear in both Figs. 5(b) and 5(c). In Fig. 5(c), more details could be observed after dehazing, but the whole image displays unnatural colors. In comparison, Fig. 5(d) presented a dehazed result approaching the original scene in Fig. 2(b). Additionally, further observations can be made on the two regions labeled as A and B as examples, of which A denotes a target close to the observer and B is almost completely buried in the haze in the raw image. All three methods achieve great improvements in the dehazed images in region A. Looking more carefully at the images, one could find that only in Fig. 5(d) the buildings in region B are recovered. In Fig. 5(c), the contrast in regions with variable intensities increase more than that in Fig. 5(d), but no obvious improvements could be seen in distant regions with heavy haze interference. In other words, the method proposed in this study works better than the other methods examined in improving the detection range of sensors against haze, and the current method is able to manage haze-opaque regions to some extent in hazy images.

To show the robustness of the algorithm, another sample image was captured and dehazed. The second image shown in Fig. 6(a) focuses on a group of buildings located at almost the same distance of about 900 m. The dehazed image with the currently proposed method is shown in Fig. 6(b). Two regions in the scene are chosen and magnified in Figs. 6(c)–6(f). Buildings in the dehazed images are much easier to recognize and many details not seen in the raw image emerge after dehazing. Similar to the analysis of first scene, as selective measures of performance for these images, horizontal lines of hazy and dehazed images are generated and shown in Figs. 6(g) and 6(h).

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Fig. 7. Similarly, these histograms display noticeable improvements in the clarity of the dehazed images. More details can be distinguished by the human eye in the dehazed images. The second scene shown in Fig. 6(a) is improved through the dehazing method, but its performance is not as impressive as the first scene. This may be caused by the different viewing angles relative to the illumination source (i.e., the sun), since the airlight and direct transmission would change scatter properties.

4. CONCLUSION

A dehazing method has been described in this study based on the polarimetric information of the scene. This method guarantees the clarity of the dehazing images by addressing the low- and high-frequency components separately. To reach the separation, the hazy intensity image is decomposed by wavelet transform, and then the dehazing algorithm is conducted specially to the low-frequency parts and the high-frequency...
parts, which is processed mainly for improving the clarity. Results demonstrate that the final fused images are well dehazed and have high clarity. Comparisons with other methods also prove its excellent performance in dehazing, especially in dehazing seriously interfered regions of the images, which enables a further detection range for sensors in hazy situations.

During our research, we found that the sky regions of the dehazed images often appear overly bright, and similar issues occur in Schechner’s algorithm. This, however, does not affect our observation of the objects in the scene. Future works can still try to solve this problem and present better methods for the observation of complicated weather conditions.

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