Single Image Haze Removal: Comparative Studies with Advanced Matting Approaches

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Abstract. It is widely known that the existence of haze in the atmosphere reduces the quality of images, which are captured by sensors of camera. The haze or fog removal, called dehazing or defogging, is usually completed according to the model of physical degradation, which requires the solution of poorly posed inverse problem. To alleviate the difficulty of the inverse problem, the dark channel prior (DCP) was previously proposed and received much attention. In this paper, a DCP-based dehazing of a single input image is proposed. Considering the concerns raised in matting technology, we have replaced it by more advanced technologies, which manage the task more appropriately. After a series of experiments we decided to combine two methods forming an estimated semi-automatic algorithm for finding the corresponding values. The results on various foggy images show the strength of the proposed new algorithm.

1. Introduction

Videos and images obtained by the visual system seriously deteriorate in hazy weather conditions affecting the tracking, detection and recognition of objects at the same time compromising visual quality. Therefore, the restoration of a true scene from such hazy videos or images is of great importance.

Haze and fog are common phenomenon on land and the ocean. There are many atmospheric elements of considerable size in hazy weather conditions which cannot only absorb or disband the reflected light of the scene, but also scatter some atmospheric light to the camera. As a result an image obtained by the camera deteriorates and typically has low contrast and weak visibility [2]. Due to the deterioration of images, targets and image obstacles are difficult to identify. Obviously, this is unacceptable for automated video processing, such as extracting objects, tracking targets and recognizing objects. As a result, this is one of the main reasons for accidents in the air, at sea, in transit, etc. This therefore raises the need to develop an image dehazing algorithm to improve the environmental adaptation of visual systems. Accordingly, the progress of computer technologies, video and image dehazing algorithms has received great consideration and are widely used in civilian and military fields.

In 1976, McCartney first proposed a physical model of atmospheric scattering, founded on the Mie’s theory of scattering [3]. In the direct transmission model, the light for the image weakened by atmospheric scattering, which degrades the details of the edges and textures of the image objects. In a model with
airlight, some sunlight is scattered by the atmosphere and transmitted to the camera, these rays are not scene lit and as such they can be measured as a hazy image component whose effect is similar to the veil effect that conceal objects in the image.

Narasimhan and Nayar [4], [5] and Nayar and Narasimhan [6] assumed that the scattering coefficient has no relation to the wavelength of noticeable light in homogeneous atmosphere and represented a simplified physical model of image restoration as:

\[
I(x) = I_\infty p(x) e^{-\beta d(x)} + I_\infty (1 - e^{-\beta d(x)})
\]

where \(I_\infty\) stands for the sky brightness, \(p(x)\) denotes the normalized radiance of the scene point \(x\), \(\beta\) is the atmosphere’s scattering coefficient, and \(d(x)\) is the distance between the camera and the scene point \(x\). On the right-hand side of Eq.(1), the first element denotes the direct transmission model, the second element represents the airlight model. Eq.(1) also specifies that the proportion of the direct model will decline due to the growth in distance. This is also the reason why some remote scenes of an image look blurred on a clear day.

2. The Dark Channel Prior for Image Dehazing: a Brief Introduction

The dark channel prior (DCP) is based on the statistics of haze-free outdoor images. It has been determined that in most local areas that do not cover the sky, very often some pixels (called dark pixels) have a very low intensity in at least one color (RGB) channel. The intensity of these dark pixels in this channel is mainly provided by airlight. He et al. [1] combined the haze imaging model and the soft matting [7] interpolation method and thereby restored the high quality image without haze and created a good depth map.

He et al. [1] made more easier Eq.(1) as

\[
I(x) = J(x) t(x) + A_\infty (1 - t(x))
\]

where \(J(x)\) stands for a clear image, \(t\) denotes a transmission, whereas \(A_\infty\) represents the atmospheric light value corresponding to the object at an infinite distance, and is typically simply valued from the sky area.

In Eq.(2) there are only two unidentified parameters. If we can get the transmission \(t\) and the atmospheric light value \(A_\infty\), we will get the restored image \(J\). For the dehazing algorithm founded on the physical model, the parameters directly determine the results of dehazing. This means that the more precise the parameters are, the better the dehazing performance will be. It should be noted that the easy physical model is found on the statement of single scattering and homogeneous atmospheric environment and thus this model may not be the finest imaging model for certain cases, such as sea haze or inhomogeneous haze.

Kaiming He and his colleagues researched a large number of transparent external images and found that in most regions of the transparent outer image (with the exception of the sky region and the white region) there is a pixel channel with minimum value of zero. It is also named the dark channel prior theory. The image of the dark channel is estimated by the formula:

\[
J_{\text{dark}}(x) = \min_{c \in \{r, g, b\}} (\min_{y \in \Omega(x)} (J(y)))
\]

where \(\Omega\) stands for a square window centered at pixel \(x\), and \(r, g, b\) are respectively red, green and blue components. For a transparent image with excepting for the region of the sky and the white region, \(J_{\text{dark}} \approx 0\).
The DCP is a statistical property of outdoor haze-free images: most patches in these images should contain pixels which are dark in at least one color channel. These dark pixels can be due to shadows, colorfulness, geometry or other factors. This prior provides a constraint for each pixel, and thus solves the ambiguity of the problem. (Because) the DCP is one of the popular single image dehazing algorithms in these last years, it was chosen as a starting point.

As mentioned before, the DCP introduces an extra constraint to each pixel and it provides an estimated transmission value. A method called “matting” helps to refine this transmission map, because it has halo artifacts. To suppress these artifacts, we have implemented haze removal based on DCP with latest methods of image matting. Furthermore, most algorithms with a common grid random field often deteriorate from haze artifacts. There is no universal image statistics on natural colors which can handle the dehazing problem. The matting is a very important task in dehazing and pose a significant challenge for information engineering. We therefore, wanted to make sure that the using of DCP with advanced matting technologies will allow us to get as clear images as possible and achieve good results in image dehazing.

3. Improving DCP-Based Dehazing Performance with Advanced Matting Technologies

3.1. Natural Image Matting

Natural image matting is the extraction of a foreground object from an image. It has an essential role in image and video editing.

It is not so difficult to notice that the haze imaging Eq. (2) has an analogous form with the image matting equation:

$$I_i = F_i \alpha_i + B_i (1 - \alpha_i)$$

where $I_i$ stands for given image, $F_i$ is the unidentified foreground layer, $B_i$ is the unidentified background layer, $\alpha_i$ is the unidentified alpha matte, and $i$ is the index of pixel. By reason there are three unidentified values at each pixel $i$ with only one constraint, resulting in the problem being seriously under-constrained.

The existing natural matting methods can be mainly classified as either sampling-based methods [10] or affinity-based [7, 8, 9, 11]. If we compare them, in most cases, the principle is relatively the same but data matrices in [7] are local and weighted by a uniform data matrix, whereas in [8] the data matrices are non-local and appropriately weighted by the non-local kernel, biasing the solution towards an assumption.

KNN matting [9] does not rely on the local color-line model as in [7] and does not have the issue of kernel size as in [8]. Their approach allows the simultaneous extraction of multiple overlapping layers based on sparse input trimaps and output alphas satisfying the summation property. A sampling based image matting [10] uses a strategy to build a comprehensive set of known examples by sampling from all color distributions in recognized regions. The designing flow of information [11] from the known region to the unknown region, as well as distributing the information inside the unknown region helps to prevent several challenges that are common in natural matting.

3.2. Proposed DCP-Based Dehazing with Advanced Matting Technologies

In this article, we propose an improvement of the DCP algorithm for single image haze removal. First of all concerning the matting technology, we replaced it by advanced approaches, which manage the task more efficiently, as can be seen from the results obtained. Secondly, after a number of experiments we decided to combine two methods and estimated a semi-automatic algorithm for finding the corresponding values.
The main idea of the proposed method is the replacing of the method for obtaining matting Laplacian matrix and the adoption of appropriate data. Our algorithm is physically justified and it is able to handle remote objects even in images of heavy haze. It is worth saying that in some cases, the haze-free images contained several halo artifacts, but now they are not as significant as initially. It is not a secret that any approach using a strong hypothesis has its own constraints. The dark channel prior, may be unreasonable when the scene object is similar in nature to the airlight over a large local area and has no shadow applied to objects, but our proposed algorithm works exquisitely for most of the exterior haze images, it may fail only in some extreme situations.

3.3. Experimental Results
The soft matting algorithm [7] was applied to refine the transmission in original DCP dehazing. But then we decided to implement DCP-based dehazing with Non-local (NL) matting [8], KNN matting [9], Comprehensive sampling based matting (CSM) [10] and Information-flow matting (IFM) [11]. Fig.1 compares the results of DCP-based dehazing with advanced matting technologies.

![Figure 1. Visual comparison of DCP-based dehazing of 4 different images. (Input) Hazy images. (DCP) Original DCP dehazing. (NL) DCP-based dehazing with NL matting. (KNN) DCP-based dehazing with KNN matting. (CSM) DCP-based dehazing with CSM. (IFM) DCP-based dehazing with IFM.](image)

| 1st image | DCP | NL | KNN | CSM | IFM | NEW | Best value |
|-----------|-----|----|-----|-----|-----|-----|------------|
| Image visibility measurement (IVM) | 6.5234 | 6.8204 | 6.7790 | 7.6852 | 7.2391 | 8.1547 | max |
| Image structural similarity (SSIM) | 0.6856 | 0.5732 | 0.5829 | 0.5293 | 0.6132 | 0.5425 | min |
| Contrast gain(Cg) | 0.2512 | 0.5278 | 0.5088 | 0.5755 | 0.4416 | 0.5228 | max |
| Visual contrast measure (VCM) | 35.8696 | 35.6522 | 35.2174 | 38.4783 | 35.4348 | 41.3043 | max |
| Universal quality index (UQI) | 0.7100 | 0.6117 | 0.6138 | 0.5658 | 0.6472 | 0.5785 | min |

3.4. Improving Our Results
Since experimental results showed relatively competitive implementation, after the visual comparison and image quality assessment (Table 1), we have decided to merge soft matting algorithm [7] and IFM matting [11]. The results justified our expectation. Fig.2 shows the results of DCP-based dehazing with two merged matting technologies (NEW). The inputs are the same as was shown in Fig.1.
As shown in Table 1, DCP-based dehazing with CSM [10] is second best after DCP-based dehazing with two merged matting (NEW) [7,11], which has best IVM and VCM.

As in the previous case, Table 2 shows that DCP-based dehazing (NEW) with two merged matting [7,11] has best IVM and VCM, moreover CG is better than other values, UQI and SSIM are close to the best.

Despite the fact that the DCP-based dehazing with two merged matting shows good results after many experiments, we have estimated the semi-automatic algorithm for finding the corresponding values according to the best parameters of Image quality assessment. This allowed us to determine in what proportions to use [7] or [11]. Table 3 and Table 4 shows the improvement of NEW of 1st and 2nd images respectively.

![Figure 2. The results of DCP-based dehazing of 4 different images with two merged matting technologies.](image)

Table 3 shows that after estimating the semi-automatic algorithm for finding the corresponding values, the indicators as IVM and VCM were approximately improved by 4-5%. Despite other values being slightly deteriorated, the result looks more preferred. In the case of Table 4, IVM and VCM were approximately improved by 9-12% and the result looks better as well.
Table 2. Image quality assessment. From left to right: DCP – Original DCP dehazing, NL – DCP-based dehazing with [8], KNN – DCP-based dehazing with [9], CSM – DCP-based dehazing with [10], IFM – DCP-based dehazing with [11], NEW – DCP-based dehazing of 2nd image on Fig.2 with two merged matting.

| 2nd image | DCP       | NL        | KNN       | CSM       | IFM       | NEW       | Best value |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|
| Image visibility measurement (IVM) | 6,6781 | 5,1524 | 5,6886 | 6,7160 | 6,4465 | 8,6118 | max |
| Image structural similarity (SSIM) | 0,7297 | 0,5787 | 0,6070 | 0,5571 | 0,6520 | 0,5768 | min |
| Contrast gain(Cg) | 0,1804 | 0,3933 | 0,4154 | 0,5280 | 0,4441 | 0,5551 | max |
| Visual contrast measure (VCM) | 38,8462 | 21,9231 | 23,0769 | 24,4231 | 34,8077 | 55,3846 | max |
| Universal quality index (UQI) | 0,7698 | 0,6049 | 0,6149 | 0,5905 | 0,6622 | 0,6154 | min |

Figures 3, 4 and Tables 5, 6 show visual comparisons of different dehazing technologies and image quality assessments respectively. Proposed DCP-based dehazing with two merged matting after improvement handles the tasks in a more appropriate way and is relatively competitive among different advanced single image dehazing technologies.

Table 3. Image quality assessment after the improvement. From left to right: NEW and NEW* – DCP-based dehazing of 1st image on Fig.2 with two merged matting before and after improvement.

| 1st image | NEW | NEW* | % of improvement |
|-----------|-----|------|------------------|
| Image visibility measurement (IVM) | 8,1547 | 8,4595 | 3,7377 |
| Image structural similarity (SSIM) | 0,5425 | 0,5465 | -0,7319 |
| Contrast gain(Cg) | 0,5228 | 0,4966 | -5,0115 |
| Visual contrast measure (VCM) | 41,3043 | 43,2609 | 4,7370 |
| Universal quality index (UQI) | 0,5785 | 0,5852 | -1,1449 |

Table 4. Image quality assessment after the improvement. From left to right: NEW and NEW* – DCP-based dehazing of 2nd image on Fig.2 with two merged matting before and after improvement.

| 2nd image | NEW | NEW* | % of improvement |
|-----------|-----|------|------------------|
| Image visibility measurement (IVM) | 8,6118 | 9,3900 | 9,0364 |
| Image structural similarity (SSIM) | 0,5768 | 0,5879 | -1,8881 |
| Contrast gain(Cg) | 0,5551 | 0,5063 | -8,7912 |
| Visual contrast measure (VCM) | 55,3846 | 62,3077 | 12,5000 |
| Universal quality index (UQI) | 0,6154 | 0,6389 | -3,6782 |
Figure 3. Visual comparison of different dehazing technologies. (Input) Hazy image. (DCP) Original DCP dehazing. (NLD) Non-Local dehazing [12]. (CAP) Color Attenuation Prior dehazing [13]. (AD) Adaptive dehazing [14].

To sum it up, it is worth to say that finding universal values to qualify dehazing images is problematic and improving all parameters simultaneously might be very complicated, but on the other hand the achieved results are more in line with our expectations and visual perception is at a high level.

Table 5. Image quality assessment of 1st image. From left to right: NLD [12], CAP [13], AD [14], NEW – DCP-based dehazing of with two merged matting after improvement.

| 1st image       | NLD | CAP | AD    | NEW   |
|-----------------|-----|-----|-------|-------|
| Image visibility measurement (IVM) | 7.2506 | 7.9923 | 7.1964 | 8.4595 |
| Image structural similarity (SSIM) | 0.6151 | 0.5146 | 0.5802 | 0.5465 |
| Contrast gain(Cg) | 0.4191 | 0.5726 | 0.5241 | 0.4966 |
| Visual contrast measure (VCM) | 47.3913 | 34.7826 | 36.3043 | 43.2609 |
| Universal quality index (UQI) | 0.7718 | 0.4863 | 0.6130 | 0.5852 |

Table 6. Image quality assessment of 2nd image. From left to right: NLD [12], CAP [13], AD [14], NEW – DCP-based dehazing of with two merged matting after improvement.

| 2nd image       | NLD | CAP | AD    | NEW   |
|-----------------|-----|-----|-------|-------|
| Image visibility measurement (IVM) | 10.2234 | 6.4004 | 5.3570 | 9.3900 |
| Image structural similarity (SSIM) | 0.4866 | 0.6508 | 0.7173 | 0.5879 |
| Contrast gain(Cg) | 0.4931 | 0.4060 | 0.3724 | 0.5063 |
| Visual contrast measure (VCM) | 60.5769 | 26.7308 | 35.5769 | 62.3077 |
| Universal quality index (UQI) | 0.9046 | 0.6187 | 0.7073 | 0.6389 |
Figure 4. Visual comparison of different dehazing technologies. (Input) Hazy image. (DCP) Original DCP dehazing. (NLD) Non-Local dehazing [12]. (CAP) Color Attenuation Prior dehazing [13]. (AD) Adaptive dehazing [14].

4. Conclusion
The DCP-based dehazing of single input images with combined two matting technologies [7, 10] was proposed and the semi-automatic algorithm for finding the corresponding values was estimated. The results of various hazy images show the strength of the proposed new algorithm. We have demonstrated that the DCP-based dehazing with merged matting approaches a point where it can dramatically reduce halo artifacts, while also preserving accuracy. Therefore, the proposed method might be competitive among some advanced single image dehazing technologies.

We are sure that the development of new algorithms from different directions is extremely important and this will contribute to the further development of information engineering.

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