Image Dehazing Using Dark-Channel Prior

Introduction

Images of landscapes are often affected by disruptions in the medium. For instance, air particles and water droplets can deflect light, leading to a hazy effect in say, sunny images. Other common examples include fog, smoke and water scattering light, which increase opacity in the medium. Outdoor images are therefore prone to a loss of contrast and inaccuracies in color information. As a result, computer vision programs that assume clear, accurate images as input, suffer from bias. For example, a vehicle detection algorithm might produce undesired results if a hazy, adulterated image is fed to it. Image dehazing aims at removing unwanted haze, restoring image contrast and correcting color. The process finds use in applications such as remote sensing, video surveillance and object detection where color precision and fair contrast are required.

While several techniques exist for image dehazing, the Dark-channel prior is studied in this project. The dark-channel prior is based on the statistical observation that in the local area (i.e. the entire image area excluding the sky portion) of any outdoor image, in at least one of the color channels in each pixel neighborhood, the exist at least one pixel with a very low intensity, close to zero. Despite being reasonable and producing acceptable results, the prior has some flaws. The technique produces halo effects around edges, causes oversaturation in images where the haze is uneven or minimal and fails for images where the color of the landscape has minimal shadows and is like the sky (e.g. snowy landscapes).

In this project a dark-channel prior program titled “Defogging-Images-using-Dark-Channel-Prior” by Arun Dixit was studied, and the paper entitled "Single image haze removal using dark channel prior," by Kaiming He, Jian Sun and Xiaoou Tang, taken as a reference point. The algorithm was slightly tweaked to reduce the impact of the flaws on images with varying haze and contrast and the results were compared.

Background

Single Image dehazing is a challenging problem since the depth of different objects in the image need to be known to estimate the amount of dehazing required. This requirement is constrained in single image dehazing where no additional depth information is provided.

The equation below is commonly used in Computer vision to describe hazy images:

$$I(x) = J(x)t(x) + A(1 - t(x)) \quad (1)$$

Where:

I is the observed intensity (in other words, the hazy input)

J is the scene radiance (the brightness of the landscape)

t is the transmission, which is the amount of light reaching the camera

A is the global atmospheric light (total illumination of the landscape)

It is worth noting that the term $J(x)t(x)$ represent the scene radiance along with its attenuation in the medium. This term is called the direct attenuation. The term $A(1 - t(x))$ represents the air light, that is, scattered light and color changes that occurred as a result.

Dark-Channel prior

As mentioned above, the dark- channel prior is based on the observation of at least one pixel in at least one of the color channels of each neighborhood in the local area of an outdoor image being zero. In their study, Kaiming He et al. mention that they collected outdoor images from over 150 search engines and hand-picked the haze-free images. A sample of 500 images was taken at a time, the sky area manually extracted, and their dark channels calculated after resizing. It was found that only a minimal amount of images deviated from the Dark-Prior claim, with most pictures having a dark channel intensity close to zero. The sky area is ignored since intensities tend to be higher in that region.

To formally describe the dark channel, the equation below was introduced in the reference paper. (Kaiming He, Jian Sun and Xiaoou Tang,2009).

$$J^{dark}(x) = \min_{y \in \Omega(x)} (\min_{c \in \{r, g, b\}} J^c(y)) \qquad (2)$$

Where:

J^{dark} is the dark channel of an arbitrary image.

J^c is a color channel in J.

$\Omega(x)$ is a neighborhood of pixels centered at x.

Note: The 2 minimum operations are commutative.

In other words, according to the dark channel prior, for an outdoor haze-free image,

$$J^{dark}(x) \rightarrow 0 \qquad (3)$$

In hazy images, the air light value is greater, and transmission is lower than in haze-free images since light is being scattered and reaches the camera in reduced amounts. This results in increased brightness in hazy images, which in turn increases the intensity of their dark channels. Therefore, the intensity of a dark channel is a rough approximation of the thickness of the haze.

Dark-Channel Prior Dehazing Procedure

Dehazing comprises of several steps. Some are slightly different in the reference paper and in the program used. However, both the paper and the program follow the same steps broadly. While studying the program, it was found that the description in the readme file was slightly misleading in that it suggested that a Fourier transform was used. However, upon reading the haze_removal.py script, no Fourier transform was found, and the operations were all carried out in the spatial domain. The paper on the other hand, gives a theoretical definition of each step, with derivations for each formula used in each step. The steps outlined here will ignore this misleading information and will describe dehazing as it is being carried out in the code script, while providing more information and explaining derivations where required.

1. Calculating the dark channel

The formula for the dark channel in (2) is applied in this step. Each neighborhood in the image is looped through and the lowest intensity pixel is selected to build the dark channel. For clarity purposes, Figure 1b. below shows the dark channel of Figure 1a.

Figure 1a. Original picture

Figure 1b. Dark-Channel map

2. Estimating the air light

As mentioned above, the intensity of the dark channel is a measure of the haze thickness. Using this observation, the air light, which is the scattered light can be estimated by the higher intensity of the pixels in the dark channel. The intensities of the dark channel image are therefore sorted, and the 0.1% pixels selected, and the mean selected. The mean represents the estimation for the air light.

3. Estimating transmission

Considering the hazy image equation for each color channel below:

$$I^c(x) = t(x)J^c(x) + A^c\,(1 - t(x)) \quad (4)$$

We first normalize each color channel:

$$\frac{I^c}{A^c} = \frac{t(x)J^c(x)}{A^c} + 1 - t(x) \quad (5)$$

Then, we assume that transmission in a neighborhood $\Omega(x)$ is constant, and we call this $\tilde{t}(x)$ and we calculate the dark channel on both sides.

$$min_{y\,\epsilon\,\Omega(x)}\left(min_c \frac{I^c(y)}{A^c}\right) = \tilde{t}(x)\, min_{y\,\epsilon\,\Omega(x)}\left(min_c \frac{J^c(y)}{A^c}\right) + 1 - \tilde{t}(x) \quad (6)$$

Due to the dark prior,

$$J^{dark}(x) = \min_{y\in\Omega(x)}\left(\min_c J^c(y)\right) = 0 \quad (7)$$

So,

$min_{y \, \epsilon \, \Omega(x)} \left(min_c \frac{J^c(y)}{A^c} \right) = 0.$ Since A^c is always positive

Substituting in (6),

$$\tilde{t}(x) = 1 - \; min_{y \, \epsilon \, \Omega(x)} \left(min_c \frac{I^c(y)}{A^c} \right) \qquad (8)$$

However, it is important to conserve a fraction of the haze since it helps depth-perception. A certain amount of haze is always present, even in “haze-free” images and in the natural environment. We therefore introduce ω, a constant parameter representing the fraction of haze retained. This number is set to 0.95 in the paper and in the code.

$$\tilde{t}(x) = 1 - \; \omega \, min_{y \, \epsilon \, \Omega(x)} \left(min_c \frac{I^c(y)}{A^c} \right) \qquad (9)$$

In practice, that is in the script, the image is looped through, and the above equation is applied to every neighborhood of pixels.

4. Refining transmission

Assuming constant transmission leads to a rough transmission estimate throughout the image since transmission varies in different parts of the image. This results in severe halo effects and artifacts since the assumption interferes with the actual depth and edges of objects in the landscape. Therefore, after the transmission has been calculated, the transmission map that to be refined, smoothing out and rough edges and eliminating noise to reduce halo effects in the resulting dehazed image.

While soft matting is used in the “Single Image Haze Removal Using Dark Channel Prior” paper, the code uses a guided filter. Both offer comparable performance except that the guided filter operates faster, in O(N) time complexity. Both techniques are closely related to the Laplacian matrix as stated in “Single Image Haze Removal Using Dark Channel Prior” paper, on page 5, section 4.2, "Improved Single Image Dehazing Using Guided Filter" paper, on page 2 section II B. It is important to note the use of the Laplacian matrix here since its validity in image dehazing has been proved in the “Single Image Haze Removal Using Dark Channel Prior” paper, on page 6, section 4.2. Put in simple terms, when deriving the Laplacian matrix for image dehazing, it is assumed that the foreground and background colors in any pixel neighborhood, lie on a single straight line in the RGB space. This assumption, called the color line assumption, also holds for outdoor images as stated in the reference paper by Kaiming He et al.

Soft matting is a technique used to obtain the opacity of pixels at different depths of the image. It requires an input image, a trimap (a binary map clearly differentiating the foreground and background edges) and an alpha matte (a map of the alpha channel of each pixel). It produces a sort of binary depth map, with images closer in the foreground as brighter and darker images further in the background. The technique is used in image dehazing to recover depth information lost while assuming constant transmission, smoothing out noise and refining edges.

Guided filters on the other hand, are used to remove noise from an image while preserving edges. They work by analyzing the input image and adjusting their behavior according to a guidance image and producing a resulting image, free from noise and with sharper edges.

The "Improved Single Image Dehazing Using Guided Filter" paper compares the results from the two techniques, claims improved efficiency from the guided filter and proves the validity of its use for image dehazing on pages 2-3, section III B.

5. Recovering image

The final image is recovered using the formula below.

$$J(x) = \frac{I(x) - A}{\max(t(x), t_0)} + A \qquad (10)$$

Where:

J is the recovered image

I is the hazy input image.

A is the atmospheric light.

t is the transmission, bounded by , t_0 to avoid division by 0 and preserve a small amount of haze to allow for depth perception

Fallacies of Dark-channel prior- Explanations and findings

1. Snowy landscapes

As mentioned in the introduction, the dark prior fails on landscapes where air light is of the same color as the landscape features and minimal shadows exist in the landscape. This issue is inherent to the dark prior assumption since the landscape is devoid of pixels with intensities closer to zero. The images below demonstrate this case scenario. The image used to test this fallacy is a screenshot of an image taken by Memorial University of Newfoundland.

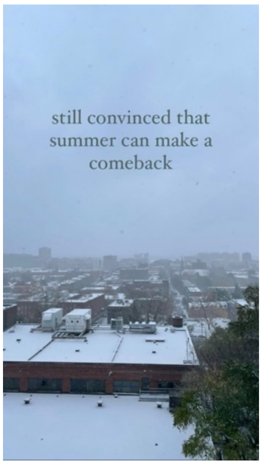

Figure 2a. snowy landscape *Figure 2b. results with snowy landscape*

2. Oversaturation

Oversaturation is expected to occur with the dark-prior since haze removal for each neighborhood is based on the darkest pixel in the neighborhood. Normally, a larger neighborhood size will produce a better dark channel and hence better results since it is expected that the darkest pixel in the larger neighborhood is darker than the darkest pixel in the smaller neighborhood.

Upon experimenting with different neighborhood sizes, it was found that the code produces the same effect, that is, oversaturation increases with decreased patch sizes.

At first, the issue was thought to be highly dependent on the hazy image used. This supposition sprung from observing the results from different neighborhood sizes in the papers and from the outputs. This idea was based on different images rendering different results with different neighborhood sizes because the sky proportions, luminosity and natural shadows vary amongst images (in other words, their dark channels vary significantly). Therefore, for the same neighborhood size, the probabilities of encountering oversaturation and inadequate haze removal are different across images.

To test this claim, different types of landscape images were selected and their results with different neighborhood sizes compared. Amongst the landscapes selected, three very different pictures, including a dark, night-time scene, an underwater image and a bright, outdoor image, and their results are shown below. The guided filter kernel size was kept constant, at 60 x 60, since this experimentation round was only testing the effects of the dark channel on oversaturation in the results.

As it can be seen, the resulting dehazed image quality varies greatly among the different images. While the sunny dehazed images in Figure 3 present a considerable amount of oversaturation in all three cases, the dehazed images of the sea snake in Figure 4 show great improvement as patch sizes are increase (almost no oversaturation for 14 x 14 patch size). As for the night landscapes in Figure 5, oversaturation cannot be observed and there are only slight changes as patch sizes are increased. However, one similarity amongst all of them is that oversaturation is reduced with lower patch sizes. Even with the night landscape, when the patch size 14 x 14 is applied, a decrease in saturation can be observed. These results support the claim that oversaturation indeed depends on the intensities in the image.

In other words, smaller neighborhoods restrict the level of detail captured. As a result, estimations of the dark channel, transmission and air light might be flawed, leading to oversaturation.

It is worth mentioning that increasing patch sizes also increases computation time. It was found that for patch sizes of 21 x 21, certain images took longer than 5 minutes to process.

Figure 3a. original image, 3b. dehazed result with patch size 3 x 3, 3c. dehazed image result with patch size 7 x 7, 3d. dehazed image result with patch size 21 x 21

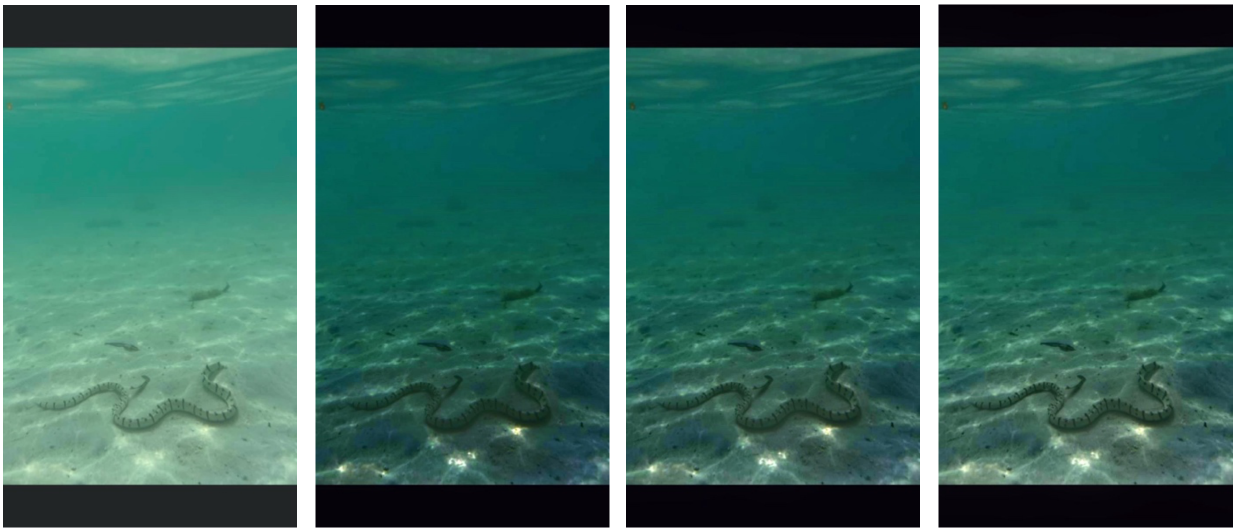

Figure 4a. original image, 4b. dehazed result with patch size 3 x 3, 4c. dehazed image result with patch size 7 x 7, 4d. dehazed image result with patch size 14 x 14

Figure 5a. original image, 5b. dehazed result with patch size 3 x 3, 5c. dehazed image result with patch size 7 x 7, 5d. dehazed image result with patch size 14 x 14

3.Halo effect

a. Experimenting with kernel size for estimations of Dark-Channel, air light and transmission

Another issue experienced with the dark prior, is the presence of halo effects in the dehazed image. Halo effects are undesired artifacts around the edges of images. They stem from the use of the guided filter. While the filter decreases time complexity and produces results comparable to soft matting, it also produces halo effects for areas with sudden depth changes. Furthermore, if increasing neighborhood sizes decreases oversaturation, it also 'fluffs out' halo effects. This is because increased neighborhood sizes do not provide the precise location of areas to be smoothed and sharpened. As a result, some areas are overly smoothed out and when they coincide with an area of varying depth, the boundary between the two is surrounded by a halo effect.

Similar to the oversaturation problem, the extent to which halo effects are affected by growing patch sizes depends on the landscapes. Indeed, landscapes with more sudden depth changes present increased halo effects.

Figures 6 and 7 are of interest since they have a sharp difference between foreground and the background with about half of the electric pole being in the sky area. The branches in Figure 7 also have a big depth gap with the sky area. A considerable amount of halo effect can be observed in both images as patch sizes increase.

In an attempt to experiment with soft matting and how the results might be affected by using soft matting instead of a guided filter, two libraries were imported and attempts to process hazy images were made. However, the expensive computations would not allow for the program to fully process images. The running kernels would be killed by the system after running for some time.

Figure 6a. original image, 6b. dehazed result with patch size 3 x 3, 6c. dehazed image result with patch size 7 x 7, 6d. dehazed image result with patch size 28 x 28

Figure 7a. original image, 7b. dehazed result with patch size 7 x 7, 7c. dehazed image result with patch size 14 x 14, 7d. dehazed image result with patch size 21 x 21

b. Experimenting with kernel size of the guided filter

So far, the kernel sizes used to estimate the air light, calculate the dark-channel and the transmission have been manipulated. The guided filter kernel was kept constant to experiment the effects of the former kernels on the results. The guided filter kernel was changed to experiment with its influence on the halo effects. The guided filter works to remove noise and smooth out edges while maintaining the image's structure. Before experimenting with the guided filter kernel, it was expected that decreasing the guided filter size would intensify halo effects since the filter would not be receiving adequate amount of information from the surroundings to process. During this round of experimentation, the other kernels were kept constant (to a size of 7 x 7) and the kernel size of he guided filter is manipulated.

As Figure 8, below demonstrates, decreasing the kernel size indeed introduces more halo effects. However, an important observation made while experimenting with the kernel is that beyond a certain kernel size, the filter overly smoothes out the image. While the halo effects are reduced in certain areas (usually deeper in the local area), they 'fluff out' in other regions, namely close to the sky area, where depth changes are abrupt with foreground objects. An explanation for this might be similar to the explanation above where the large neighborhood size fails to provide precise edge information, which results in a loss of detail when the guided filter is applied.

Figure 8a. original image, 8b. dehazed result with patch size 3 x 3, 8c. dehazed image result with patch size 60 x 60, 8d. dehazed image result with patch size 100 x 100

Figure 9a. original image, 9b. dehazed result with patch size 3 x 3, 9c. dehazed image result with patch size 60 x 60, 9d. dehazed image result with patch size 100 x 100

Conclusion

The Dark Channel Prior is a simple and effective method of dehazing single images. The use of the guided filter improves computation and running time, while producing results comparable to soft matting. However, the Dark Channel Prior technique requires fine tuning for different images. The trade-offs between computation time and patch size should also be considered. While increasing patch sizes correct oversaturation to some extent, it also increases halo effects. Therefore, a fine balance should be found be found between the amount of oversaturation and halo effect to be tolerated. Ultimately, the fine tuning of the parameters depends on the purpose of image dehazing.

References

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Contributions

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