Fast Single-image Defogging

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Bad weather conditions such as fog, haze, and dust often reduce the performance of outdoor cameras. To improve the effectiveness of surveillance and in-vehicle cameras under such conditions, we propose a method based on a dark channel prior for quickly defogging images. It first estimates the intensity of the atmospheric light by searching the sky area in the foggy image. Then it estimates the transmission map by refining a coarse map from a fine map. Finally, it produces a clearer image from the foggy image by using the estimated intensity and the transmission map. When implemented on a notebook PC with a graphics processing unit (GPU), it was able to process 50 images (720 × 480 pixels) per second. It can thus be used for real-time processing of surveillance and in-vehicle system images.

1. Introduction

A large number of surveillance cameras for crime prevention and disaster monitoring are deployed worldwide to help maintain peace and safety. In addition, many vehicles are equipped with cameras for accident prevention or recording. However, bad weather conditions, such as fog, haze, and dust, can create many fine particles, i.e., particulate matter, with, for example, a size of 2.5 µm or less (PM 2.5) in the air. Such particles scatter the radiance from objects, which reduces camera performance, resulting in unclear images. This makes it difficult to identify such objects as moving cars, pedestrians, and license plate numbers, especially from a distance. Image defogging means removing the effects of particulate matter to improve object clarity.

Early defogging methods use not only the foggy image itself but also other information. These non-single-image defogging methods use various approaches. For example, polarization-based methods[1),2)] use two or more images taken with different degrees of polarization, depth-based methods[3),4)] use depth information obtained elsewhere, and several methods[5),6)] use multiple images of the same scene captured under different weather conditions. None of these methods is thus suitable for real-time application.

More recent single-image defogging methods use only the foggy image as input, so they are better suited for surveillance and in-vehicle applications because the input video can be defogged frame by frame. However, the computational load for estimating the intensity of the atmospheric light and the medium transmission map, which represents the portion of light from objects that is not scattered and thus reaches the camera, is quite high.

We have reduced the computational load and thus the run time for image defogging while maintaining good defogged image quality. Two simple filters are combined on the basis of local pixel information and used to estimate the transmission map. This enables our single-image defogging method to run about 100 times faster than the reference method, making it well suited for application to surveillance systems and in-vehicle systems.

This paper is organized as follows. In the next section, we introduce the image defogging model, discuss previous methods, and describe the dark channel prior. Our fast single-image defogging algorithm is then described, and the implementation and application are discussed.

2. Background

2.1 Image defogging model

The image defogging model can be described as

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

where x is the pixel location, $I(x)$ is the foggy image, $J(x)$ is the scene radiance, i.e., the defogged or clarified image, $t(x)$ is the transmission map, which shows how much of the light in the scene radiance is not scattered by fog or haze particles and reaches the camera, and A is the atmospheric light intensity, which is assumed to be the same for every pixel. The $J(x)t(x)$ term represents the direct attenuation, i.e., how much of the scene information reaches the camera without scattering. The $A(1-t(x))$ term represents "air light," i.e., how much the atmospheric light contributes to the foggy image.

Figure 1 shows the image defogging model. First, the transmission map $t(x)$ and the intensity of the atmospheric light are estimated for input foggy image $I(x)$. Then, clarified image $J(x)$ is recovered from $I(x)$. This is an ill-posed problem because three unknowns, $t(x)$, A, and $J(x)$, need to be resolved from only one known, $I(x)$.

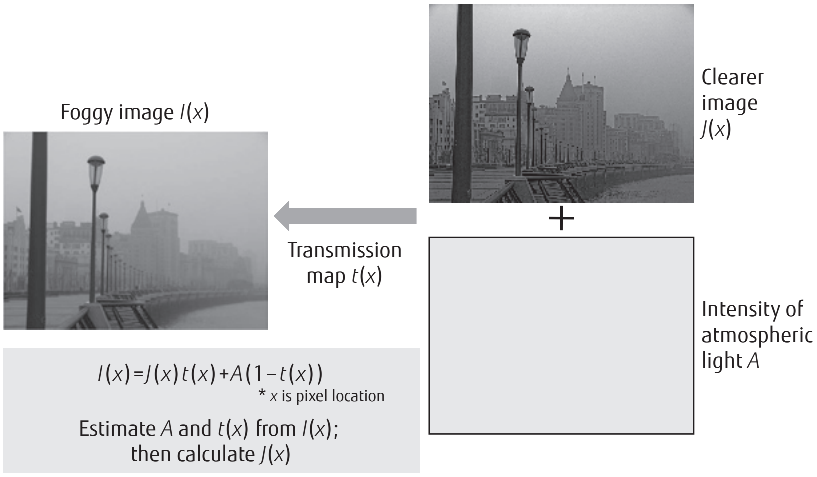
The transmission map for an object shows the attenuation in the atmosphere and can be described as

$$t(x)=e^{-\beta d(x)},$$

where β is the atmospheric scattering coefficient, and $d(x)$ is the distance from the object to the camera. The objects in an image have different distances from the camera, so $t(x)$ varies between objects. Near objects have higher values, and far objects have lower values. The transmission map also represents the fog density. The density is higher for far objects and lower for near objects. Therefore, accurately estimating the fog density from object to object is difficult, especially for edges with abrupt changes.

2.2 Previous single-image defogging methods

Most single-image defogging methods use priors or rely on assumptions to solve the ill-posed problem. For example, Tan's method[7] is based on the assumption that images without fog or haze have higher contrast than ones with fog or haze, so fog is removed by maximizing the image contrast. Fattal's method[8] is based on the assumption that the transmission and surface shading are locally uncorrelated, so defogging is done by estimating the scene albedo and then inferring the transmission map. The method of Kratz et al.[9] is based on the assumption that the scene albedo and scene depth are statistically independent components, so the image is factorized into scene albedo and depth using a Markov random field model. The method of He et al.[10] uses a dark channel prior based on statistics for outdoor haze-free images, and haze is removed by estimating a coarse transmission map and then refining



Estimate fog density for each pixel and then remove fog (lighter for near objects; heavier for far ones).

Figure 1
Image defogging model.

it. Tarel et al.[11] assumed that the atmospheric veil is positive and less than the minimum value of the components in $I(x)$, so their method uses a median filter to obtain the atmospheric veil.

Among these methods, He's method has the simplest algorithm framework and the best defogging quality. However, it takes 10–20 seconds to process a 600 × 400 pixel image on a PC with a 3.0-Hz Intel Pentium 4 processor, so the run time is too long for surveillance and in-vehicle applications.

2.3 Dark channel prior

He et al.[10] discovered the dark channel prior, which is an assumption based on their examination of haze-free outdoor images. It represents the finding that, in most non-sky image areas, at least one color channel has pixels with very low intensity. The dark channel is defined as

$$I^{\mathrm{dark}}(x) = \min_{c\in\{r,g,b\}}(\min_{y\in\Omega(x)} I^c(y)),$$

where I^c is a color channel of I, and $\Omega(x)$ is a local area centered at x.

They examined 5000 daytime haze-free images and found that about 75% of the pixels in the dark channels had zero values and that the intensities of 90% of the pixels were below 25 (maximum value was 255). They attributed the low intensity in the dark channel to three factors: shadows, colorful objects, and dark objects.

The dark channel for foggy images is not as dark. A foggy image is brighter than the corresponding clear image due to the added air light. The dark channel for a foggy image will thus have higher intensity. This means that the intensity of the dark channel represents the fog density and also the object's distance from the camera in a way.

3. Our Algorithm

3.1 Overview

Our fast image defogging algorithm is based on the dark channel prior. If we derive the dark channel by using the image defogging model described in Section 2.1, it will look like

$$I^{dark}(x)=J^{dark}(x)t(x)+A^c\,(1-t(x)),$$

where $I^{dark}(x)$ is the dark channel for the foggy image, $J^{dark}(x)$ is the dark channel for the clear image, and A^c represents the color channel of atmospheric light. As most of the intensity values of the dark channel for the clear image are zero, this equation can be rewritten as

$$I^{dark}(x)\approx A^c(1-t(x)).$$

The transmission map can be estimated by using a transformed version of this equation:

$$t(x)\approx 1-I^{dark}(x)/A^c.$$

The $t(x)$ for the sky area in a foggy image is nearly zero as that area is at an infinite distance, which means that the color value of the sky is very similar to the intensity of the atmospheric light.

The image defogging framework is shown in **Figure 2**. First, the intensity of the atmospheric light is estimated for input foggy image $I(x)$. Then, the transmission map $t(x)$ is estimated using A and $I(x)$. Finally, the image is clarified in accordance with the image defogging model.

3.2 Estimate intensity of atmospheric light

The intensity of the atmospheric light is estimated by first identifying the top 0.1% brightest pixels in the dark channel ($I^{dark}(x)$). From among these pixels, the one with highest intensity is selected as the one representing the atmospheric light. An image showing the estimated light intensity is shown in **Figure 3**.

3.3 Estimate transmission map

The method for estimating the transmission map

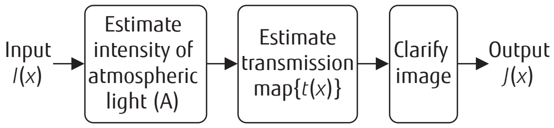


Figure 2
Image defogging framework.

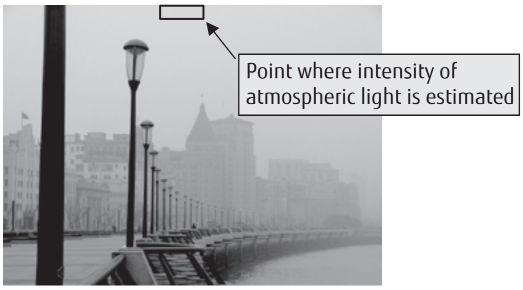


Figure 3
Estimated intensity of atmospheric light.

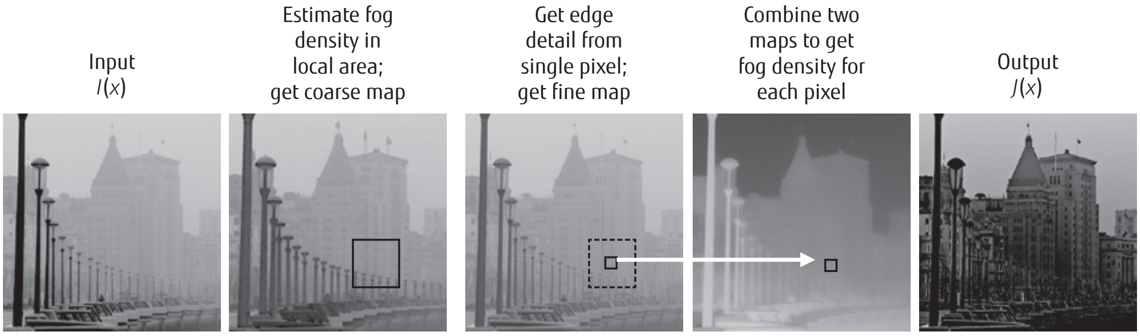


Figure 4
Method for estimating transmission map.

is illustrated in **Figure 4**. First, a coarse map representing the fog density in a local area is obtained from the input foggy image. Next, a fine map representing detailed image edge information is obtained. Finally, these two maps are combined to create a precise transmission map $t(x)$ representing the fog density for each pixel.

We call a dark channel based on a local area a coarse map:

$$M^{coarse}(x)=\min_{c\in\{r,g,b\}}(\min_{y\in\Omega(x)} I^c(y)).$$

The method first looks for the minimum value in a local area in the R, G, and B channels and then replaces the current pixel value with this minimum value.

If edge detail information cannot be obtained, meaning that the coarse map is used as $t(x)$, the final image will have noticeable halo effects, as shown in **Figure 5**. Various edge preserving filters, such as a bilateral filter[12)] and a guided filter[13)] have been proposed for overcoming this problem. However, using these filters takes much time.

We use a simpler method to solve this problem. A fine map with minimum values for the R, G, and B channels is derived to represent the edge detail information of the foggy image.

$$M^{fine}(x)=\min_{c\in\{r,g,b\}} I^c(x)$$

The coarse map is then refined by using this fine map by searching a local area centered at x in the coarse map for the pixel at location x in the fine map that has the most similar value. This can be done by looking for the pixel with the maximum value in the block in the coarse map and then selecting the pixel with the minimum one compared with the value of the pixel at x in the fine map:

$$M^t(x)=\min(\max_{y\in\Omega(x)} M^{coarse}(y), M^{fine}(x)).$$

Figure 5
Defogged image with halo effects.

Transmission map $t(x)$ is thereby obtained:

$$t(x)=1-\omega\cdot M^t(x)/A,$$

where ω is the defogging parameter, which is less than 1 and greater than 0. This parameter represents how much the image should be defogged. With a value of 0.9, a very small amount of fog would be kept for the distant objects. The smaller the value, the greater the amount of fog that is kept.

3.4 Clarify image

Finally, the image is clarified:

$$J(x)=(I(x)-A)/\max(t(x),t_0)+A,$$

where t_0 is set to a constant value to avoid dividing by zero.

4. Implementation

The transmission map estimation consumes the most time in the image defogging framework. Since our method uses only local information, i.e., the intensity of the pixel at location x, the image can be processed pixel by pixel. This facilitates parallel processing, so the framework can be implemented on a GPU. The intensity of the atmospheric light is initially estimated on the CPU, and then the foggy image and intensity of the atmospheric light are input into GPU memory. The GPU fetches these data from memory as textures, performs the necessary processing, and then renders the defogged image into the frame buffer in GPU memory. The implementation framework is illustrated in **Figure 6**. When implemented on a notebook PC with an Intel i5 2.53-GHz CPU and a NVIDIA GeForce 310M GPU, it was able to process 50 images (720 × 480 pixels) per second.

An example processing result is shown **Figure 7**. As shown in (c), the foggy effect was removed, especially in the distant parts.

5. Conclusion

We described our method for quickly defogging images, which is based on the dark channel prior. The key step is estimating the transmission map by refining a coarse map from a fine map using only local information. It thus runs about 100 times faster than the reference method while achieving the same level of image clarity. It is thus suitable for application to surveillance and in-vehicle systems.

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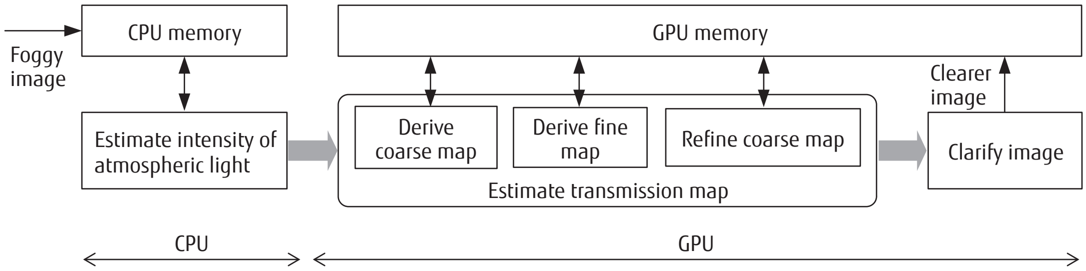

Figure 6
Implementation of fast image defogging.

(a) Foggy image (b) Foggy part (c) Defogged image (d) Clearer part

Figure 7
Example image defogging result.

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