Mobile Atmospheric Sensing using Vision Approach

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Abstract. Air quality monitoring, especially the atmospheric phenomenon of thick haze, has been an acute problem in most countries and a hot topic in the atmospheric sensing. Recently thick haze occurs more frequently in most cities of China due to the rapid growth of traffic, farming, wildfires, and industrial development. It forms a low-hanging shroud that impairs visibility and becomes a respiratory health threat. Traditionally the dust, smoke, and other particles in relatively dry sky are reported at fixed meteorological stations. The coverage of these sampling stations is limited and cannot accommodate with the emergent incidence of thick haze from industrial pollution. In addition, the visual effect of thick haze is not yet investigated in the current practice. Thick haze appears colorful veil (e.g., yellowish, brownish-grey, etc) in video log images and results in a loss of contrast in the subject due to the light scattering through haze particles. This paper proposes an intuitive and mobile atmospheric sensing using vision approach. Based on the video log images collected by a mobile sensing vehicle, a Haze Veil Index (HVI) is proposed to identify the type and severity level of thick haze from the color and texture perspective. HVI characterizes the overall veil effect of haze spatially. HVI first identifies the haze color from the color deviation histogram of the white-balanced hazy image. The white-balancing is conducted with the most haze-opaque pixels in the dark channel and seed growing strategy. Then pixel-wise haze severity level of atmospheric veil is inferred by approximating the upper veil limit with the dark color of each pixel in a hazy image. The proposed method is tested on a diverse set of actual hazy video log images under varying atmospheric conditions and backgrounds in Wuhan City, China. Experimental results show the proposed HVI is effective for visually atmospheric sensing. The proposed method is promising for haze monitoring and prediction in UAV and satellite remote-sensing images.

1. Introduction

Air quality monitoring, especially the atmospheric phenomenon of thick haze, has been an acute problem in most countries and a hot topic in the atmospheric sensing. Recently thick haze occurs more frequently in most cities of China due to the rapid growth of traffic, farming, wildfires, and industrial development. It forms a low-hanging shroud that impairs visibility and becomes a respiratory health threat. Traditionally the dust, smoke, and other particles in relatively dry sky are reported at fixed meteorological stations. The coverage of these sampling stations is limited and cannot accommodate with the emergent incidence of thick haze from industrial pollution. In addition, the visual effect of thick haze is not yet investigated in the current practice. Thick haze appears colorful veil (e.g., yellowish, brownish-grey, etc) in video log images and results in a loss of contrast in the subject due to the light scattering through haze particles.

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Video log images are often collected by most state Departments of Transportation (DOTs) through contractors or internal resources because the camera sensor becomes cheaper and better in terms of the resolution and other features. State DOTs manually or automatically extract important traffic incidents from these images. Actually, those images acquired from the sensing network around the traffic scenarios can also be used to visually estimate the atmospheric quality. By mimicking human's visual perception of thick haze in the atmosphere, a Haze Veil Index (HVI) is, for the first time, proposed in this paper to identify the type and severity level of thick haze from the color and texture perspective. HVI characterizes the overall veil effect of haze through a mobile sensing vehicle. It is an intuitive report of the air quality along the routes of interest.

Relevant research can be found in the area of automate de-hazing in digital images. The automatic de-hazing algorithms can be divided into two categories: de-hazing with and without reference. Several images of the same scene are captured under different weather condition in [1-2] to make a reference for de-hazing. User inputs about the color and range of haze are incorporated into the automatic de-hazing process as the cue for single image based haze removal [3-4]. Recently, single image haze removal has made significant progresses. The success of these methods lies on using some priors or assumptions. According to McCartney's haze model [5], Tan removes haze by maximizing the local contrast of the restored image, based on his observation that a haze-free image has higher contrast compared with the hazy image [6]. The results are visually compelling although they tend to be saturated. Fattal estimates the Aledo of the scene and the medium transmission under the assumption that the transmission and the surface shading are locally uncorrelated [7]. This approach is physically sound and can produce impressive results. However, it cannot handle heavily hazy images well and may fail in the cases where the assumption is broken. He Kaiming et al propose a novel prior—Dark Channel Prior (DCP) —for single image haze removal [8]. The dark channel prior is based on the statistics of outdoor haze-free images. he find that, in most of the local regions except for the sky, some pixels (called dark pixels) very often have very low intensity in at least one color (RGB) channel of a local patch. The intensity of these dark pixels in that channel of hazy image is mainly contributed by the air-light. Therefore, these dark pixels can directly provide a coarse estimation of the depth and haze transmission. To cope with the halo and block effect of dark channel prior, the soft matting interpolation [9] and the haze imaging model are integrated in the algorithm to recover a high-quality haze-free image and to produce an accurate depth map. Tarel and Nicolas propose a fast visibility restoration algorithm from a single image using the atmospheric veil inference of hazy image [10]. It works for some gray or colorful images with haze. However, none of the above focuses on the visual evaluation of atmospheric quality by characterizing the polluting veil effect of haze in the atmospheric images. Therefore, there is a need to characterize the visual effect of haze in the atmosphere using the vision approach.

2. Dark channel prior (DCP) of hazy atmosphere

In this section, a brief overview of He's dark channel prior (DCP) of haze characterization [8] is given.

According to the widely used model [5] of the effect of the haze in an image, the observed intensity and actual scene radiance have the following relationship.

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

where I, J, A are the observed intensity, scene radiance, and atmospheric light respectively; t(x) is the portion of medium transmission at point x that is not scattered and reaches the camera. Usually t(x) attenuates exponentially with the depth in the scene. The t(x) set of all points in an image composes its transmission map. The purpose of de-hazing is to recover J by estimating the global A and t for all points of an N-pixel color image. It is an ill-posed problem because there are 3N constraints and 4N+3 unknowns in the image.

To characterize a hazy image, the statistics of DCP is introduced to estimate the haze transmission map. The DCP statistics assumes that the minimum intensity for different color channels in a patch of the image is very low and close to zero, i.e., the low intensity assumption in the dark channel.

The dark channel J^{dark} is defined as

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

where J^c is a color channel of J and $\omega(x)$ is a local patch centered at x. The dark channel is performed over pixels in the patch of different color channels.

Due to the shadows, colorful and/or dark objects / surfaces (e.g., green plant, blue water, dark road surface, etc) in the natural outdoor images, the low intensity assumption in dark channel means that, except for the sky region, the outdoor haze-free images are usually colorful and full of shadows, i.e.,

$$J^{dark} \to 0, \tag{3}$$

which is called Dark Channel Prior (DCP).

3. Mobile atmospheric sensing using vision approach

Based on the DCP of hazy atmospheric image, Haze Veil Index (HVI) is proposed in this section to visually characterize the haze of different color in the atmospheric images.

3.1. White balance of hazy atmospheric imagery

The color of heavily polluted haze in an image results from the reflectance of particles and chemicals in the atmosphere. Due to the different spectral characteristics and extinction effects in the atmosphere, the collected hazy video log image becomes colorful or grayish. Unlike the white atmospheric veil in a hazy image, the veil of a hazy image tends to be yellow or heavy gray depending on the composite of the pollutants in the atmosphere, as shown in figure 1. Therefore, it is necessary to adjust the white balance of a hazy video log image and to ensure its being pure white, i.e., the saturation for colorless pixels is close to zero.

Starting with the top 0.001 percent most haze-opaque pixels S in the dark channel of I for a medium patch size of 15*15, we grow up pixels of atmospheric veil color by the following Euclidean color distance in the RGB space.

$$\|P_j - S_i\| = \left(\sum_{c\in r,g,b}(P_j^c - S_i^c)^2\right)^{1/2} \le C_{thr}, \quad S_i \in S \text{ and } P_j \in P \tag{4}$$

where P is the neighborhood of S with a color deviation of less than C_{thr} from S in the observed hazy image I. The larger C_{thr} is, more pixels will be chosen as atmospheric veil pixels. Based on our experiments, it is suitable to set $C_{thr} = 5$. Obviously, the growing of the most haze-opaque pixels along the similar color direction gives robust estimation of the atmospheric light of a colorful or grayish hazy video log image. It stops at a less haze-opaque pixel in the direction.

With the grown haze-opaque color region, the dark channel based white balance of hazy image can be conducted by

$$WB^c(I) = \frac{I^c(x)}{A^c} = \frac{J^c(x)}{A^c} t(x) + 1 - t(x), \ \ c \in \{r, g, b\} \tag{5}$$

where A^c is the average color value in the grown haze-opaque color region, and WB(I) denotes the result of white balance of I for each color channel c.

3.2. Haze veil index

The primary cue for visual sensing of atmospheric quality by video log images is that 1) hazy pixels can usually be distinguished by the overall veil in the atmosphere; 2) hazy pixels differ with pixel depth, but are locally smooth except along edges with large depth jumps. Therefore, finding the overall atmospheric veil in the hazy video log image is the quantitative measure of atmospheric quality.

Let

$$W(x) = \min_{c \in \{r,g,b\}} WB^c(I), \tag{6}$$

where W(x) denotes the loose upper limit of the atmospheric veil of the white-balanced hazy image $WB^c(I)$ of I for channel c. Unlike the patch-wise dark channel prior, W(x) is based on pixel-wise minimal (dark) color value of a pixel. To characterize the haze veil effect, we must smooth the noise of W(x) while preserving its large jumps along edges. Following [10], one way to restrict the upper limit of the atmospheric veil is to filter W(x) with a median filter and lower W(x) to the middle of its variation, i.e.

$$\begin{aligned} A(x) &= median_{S_v}(W(x)), \\ B(x) &= A(x) - median_{S_v}(|W(x) - A(x)|), \\ V(x) &= \max(\min(p * B(x), W(x)), 0) \end{aligned} \tag{7}$$

where $A(x)$ is the robust average of W(x), $median_{S_v}(|W(x) - A(x)|$ is the robust approximation of the variation of W(x), B(x) is the estimated upper limit of the atmospheric veil, $p = 0.95$ is strength control factor of veil approximation, and $S_v = 11$ is support region for the pixel-wise W(x) analysis. Actually the atmospheric veil V (x) is inferred as a percentage of the difference between the local average of W(x) and of the local standard deviation of W(x) on a pixel-wise level.

Based on V(x), we define the haze veil index (HVI) as follows

$$HVI = \sum_c \sum_x A^c * V(x)(M * N * C)^{-1}, \tag{8}$$

where M, N, and C is the number of rows, columns, and channels in the video log image. HVI is the weighted veil of the image and ranges between 0 and 1. It identifies the type and severity level of thick haze from the color and texture perspective.

4. Experimental results

In this section, the proposed HVI is tested in terms of its consistency with the human perception of the atmospheric quality. Most of the video log images are collected by the sensing vehicle of Wuhan University, China, as shown in figure 1. It consists of such sensors as GPS/IMU, LiDAR, Panorama camera, video / infrared camera, and two CCD camera on the front-left and front-right side of the vehicle. We also collect some hazy atmospheric image from the website http://image.baidu.com. The dataset includes a diverse set of actual hazy video log images under varying atmospheric conditions and backgrounds that are taken in Wuhan City.

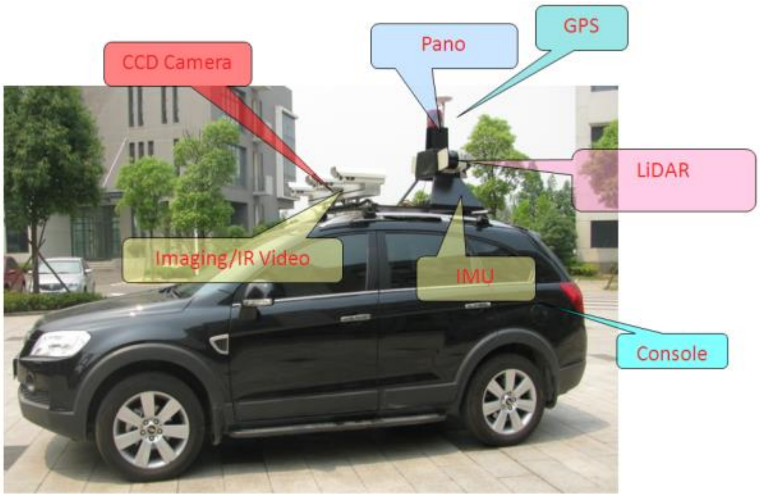
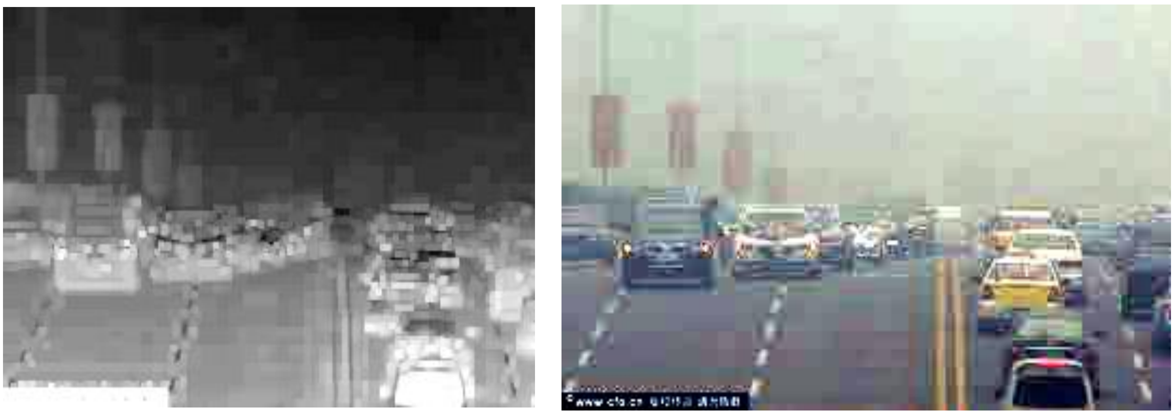


Figure 1. Sensing vehicle of Wuhan University

Figure 2 shows the result of the proposed HVI. It has a HVI of 0.82 for the hazy atmospheric image of figure 2(a), and more than 82% of the pixels are covered by the haze veil in figure 2(c). figure 2(b) is the white-balanced result of the hazy image. Compared with figure 2(a), we can see that the yellow haze veil is successfully removed. Therefore, HVI is suitable for different color of haze in the atmosphere. If we remove the haze veil from the hazy atmospheric image, we can get the result in figure 2(d). The most haze-opaque pavement area becomes clear after the haze veil, and most of the pixels are recovered from the haze veil effect. HVI coincides well with human perception of human perception of atmospheric quality.

(a) Hazy atmospheric image (b) White-balanced image



(c) Pixel-wise haze veil (d) Recovered image after veil removal

Figure 2. Results of haze atmospheric image of HVI = 0.82

Similarly, we made the comparative test on a total of 200 video log images by calculating the quantitative HVI and surveying the subjective rating of atmospheric quality. It turns out that an image with HVI greater than 0.6 is severely polluted by haze veil based on the subjective judgment. There is a high correlation between HVI and subjective rating. Therefore, HVI demonstrates its potential to visually sense the atmospheric quality.

5. Conclusions and Recommendations

This paper proposes an intuitive and mobile atmospheric sensing using vision approach. Based on the video log images collected by a mobile sensing vehicle, a Haze Veil Index (HVI) is proposed to identify the type and severity level of thick haze from the color and texture perspective. HVI characterizes the overall veil effect of haze spatially. HVI first identifies the haze color from the color deviation histogram of the white-balanced hazy image. The white-balancing is conducted with the most haze-opaque pixels in the dark channel and seed growing strategy. Then pixel-wise haze severity level of atmospheric veil is inferred by approximating the upper veil limit with the dark color of each pixel in a hazy image. The proposed method is tested on a diverse set of actual hazy video log images under varying atmospheric conditions and backgrounds in Wuhan City, China. Experimental results show the proposed HVI is effective for visually atmospheric sensing. The proposed method is promising for haze monitoring and prediction in UAV and satellite remote-sensing images.

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