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Fast Haze Removal of Fixed-point Camera Images Using Temporal Update of Transmission Map

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***Abstract*—Outdoor images are often degraded by atmospheric phenomena such as haze, fog, smoke, etc. The algorithm of recovering contrast and color fidelity of such images is called haze removal. The purpose of this paper is to propose fast haze removal algorithm designed for the time-series images captured by a fixed point camera such as surveillance. In the proposed method, the difference information of successive two images is used for updating the transmission map, although only the first image should be de-hazed by using the conventional single-image haze removal algorithm proposed by Kaiming He, et al., or dark channel prior. The advantage of our method is to reduce the processing time of transmission map generation significantly, preventing deterioration of the resulted images compared with the iterative application of He's conventional method to each video frame. It is verified through several experiments that the proposed temporal update is approximately 10 times faster than the conventional transmission map generation using guided image filters.**

Keywords—haze removal, surveillance camera, time-series images, transmission map

I. Introduction

The algorithm of recovering contrast and color fidelity of images degraded by some atmospheric phenomena such as haze, fog, smoke, and so on is called haze removal, and various algorithms have been proposed so far. Among other things, single-image haze removal proposed by Kaiming He [1] is well known for its convenience and high efficiency, and its variants are often used in developing haze removal systems and algorithms in various circumstances. However, the processing time of haze removal is still not fast enough to apply the algorithm to time-series images obtained from real-time video cameras, such as surveillance cameras. Since generating a transmission map usually occupies a large amount of the total processing time, a lot of efforts to achieve fast transmission map generation have been made so far, for example, by improving the algorithm [2], [3] and by introducing GPUs to achieve real-time processing [4].

In this paper, we propose a fast haze removal algorithm designed for the time-series images captured by fixed point camera. In the proposed method, the difference information of successive two images is used for updating the transmission map, although only the first image should be de-hazed by using the conventional single-image haze removal algorithm using dark channel prior (hereinafter this is called He's algorithm). The main advantage of the proposed method is to reduce the processing time of transmission map generation significantly, without allowing the resulted images to be deteriorated too much, compared with the conventional single-image algorithm.

The remaining part of this manuscript is organized as follows. In Section II., the outline of the conventional haze removal algorithm using dark channel prior, which is called He's algorithm below, is described. In Section III., temporal update of the transmission map is derived from the generation model of hazy image. In Section. IV., performance of the proposed temporal update is compared with the conventional method to verify the expected reduction of the processing time through several experiments. Finally, concluding remarks and some future work are mentioned in Section V.

II. Single Image Haze Removal

A. Model of Haze Image Generation

When considering the algorithm of haze removal, the following model is widely used to describe the generation of a hazy image:

$$\boldsymbol{I}(x,y) = \boldsymbol{J}(x,y)t(x,y) + \boldsymbol{A}\big(1 - t(x,y)\big), \qquad (1)$$

where $\boldsymbol{I}$ is the observed image with haze, $\boldsymbol{J}$ is the ideal scene image without haze, $\boldsymbol{A}$ is the global atmospheric light (color of haze), $t(x,y)$ is the transmission map representing the portion of the light that reaches the camera without scattering. The bold letters, $\boldsymbol{I}, \boldsymbol{J}, \boldsymbol{A}$, represent 3-dimensional vectors that consists of R, G, and B components, whereas t is a scalar commonly used for three components. The principle of haze image generation is the same as that of alpha blending. In case of haze image generation, each pixel of J is blended with haze color A by using alpha blending. In equation (1), the haze becomes denser in the area where t is closer to 0. The purpose of haze removal is to obtain the ideal image $\boldsymbol{J}$ from the observed hazy image $\boldsymbol{I}$ through Eq.(1) by estimating the atmospheric light $\boldsymbol{A}$ and the transmission map $t(x,y)$.

B. Single-image Haze Removal Using Dark Channel Prior

Kaiming He et al. proposed an efficient way of estimating atmospheric light and transmission map by using the dark channel prior [1], and many variants of the algorithm have been developed so far. The original algorithm described in [1], called He's algorithm, is outlined in this section, since it is applied only

to the first frame of successive hazy images in the proposed haze removal. Moreover, for the restoration of hazy image sequence, it is a common way to apply He's method to each hazy frame iteratively.

The first step of He's algorithm is to obtain a dark channel image I^{dark} from the observed color image $\boldsymbol{I} = (I^r,\ I^g,\ I^b)^T$, by the following equation:

$$I^{dark}(\mathbf{x}) = \min_{c\in\{r,g,b\}}\left(\min_{\mathbf{y}\in\Omega(\mathbf{x})}(I^c(\mathbf{y}))\right), \tag{2}$$

where $\Omega(\mathbf{x})$ is an $n \times n$ window whose center is located at pixel $\mathbf{x}$. We selected $n = 5$ for all the experiments described in Section IV.

Secondly, the atmospheric light and transmission map are estimated from the dark channel image I^{dark}. The atmospheric light $\boldsymbol{A} = (A^r, A^g, A^b)^T$ is calculated by using the top 0.1 % brightest pixels in the dark channel image since the dark channel of a hazy image approximates the haze denseness especially in case of outdoor scene. Using the estimated atmospheric light, the initial coarse transmission map can be calculated by the following equation:

$$\tilde{t}(x) = 1 - \omega \min_{c\in\{r,g,b\}}\left(\min_{\mathbf{y}\in\Omega(\mathbf{x})}\left(\frac{I^c(\mathbf{y})}{A^c}\right)\right), \tag{3}$$

where ω is a parameter satisfying $0 < \omega < 1$. The parameter ω controls the amount of haze removal. If you set ω = 1, you can remove the haze completely, but it will produce a visually unnatural image. Therefore, it is usually desirable that a little haze should remain. In the paper, ω is always set to a value of 0.8, since good results were obtained in all the experiments when ω = 0.8.

Finally, the coarse map $\tilde{t}(x)$ is refined so that it reflects the precise location of edges contained in the various objects in the scene. In Ref. [1], a coarse transmission map is refined by the soft matting process, which needs to solve a large-scale linear system and therefore takes a lot of processing time. To improve the situation, He et. al. suggested in [4] that the guided image filter should be used, instead of soft matting, to reduce the cost of transmission map generation. Following the suggestion, we used a fast version of guided image filter [5] for all the experiments in Section IV. The fast guided filter is used also for the conventional He's method, in order to make a fair comparison in the experiments.

III. Haze Removal Algorithm for Time-series Images

A fast haze removal algorithm for time-series images is proposed in this section. The main target of our proposal is to reduce the processing time of haze removal significantly. This is achieved by temporal update of successive transmission maps, using difference information between two successive hazy images.

A. Assumption of the proposed method

In the proposed method, it is assumed that hazy images are obtained from a fixed-point camera such as live camera for weather observation or surveillance, and therefore, they contain a common static background. In addition, it is also assumed that the light condition does not change drastically.

These conditions are roughly true if the image sequence is limited to a very short time period, such as a few seconds. For this reason, the update of transmission maps should be initialized every few seconds just like the intra frames in MPEG video compression. We believe that, even in such situations, the proposed method is still effective in processing time reduction, because at least 30 - 90 images are contained even in a few-second video. Moreover, we need to consider the deterioration of transmission maps caused by accumulation of temporal updating errors. To verify the quality of transmission maps, we compare the resulted transmission maps with the conventional results, that is, the iterated application of He's method to each video frame.

B. Temporal Update of Transmittion Map

The equation of updating the transmission map temporally can be derived from the haze image model described in Section II.A. Applying Eq. (1) to the successive two hazy frames, the following two equations are obtained:

$$\boldsymbol{I}_k(x,y) = \boldsymbol{J}(x,y)\hat{t}_k(x,y) + \boldsymbol{A}\big(1 - \hat{t}_k(x,y)\big), \tag{4}$$

$$\boldsymbol{I}_{k+1}(x,y) = \boldsymbol{J}(x,y)\hat{t}_{k+1}(x,y) + \boldsymbol{A}\big(1 - \hat{t}_{k+1}(x,y)\big), \tag{5}$$

where $\hat{t}_k$ is the k-th transmission map filtered with a guided image filter to improve the quality of the map. Since we have an assumption that the camera is fixed, the ideal scene image can be considered constant during a short time period. Note that we are therefore using a common $\boldsymbol{J}$ in Eq. (4) and (5) instead of using $\boldsymbol{J}_k$ and $\boldsymbol{J}_{k+1}$. Moreover, we also assume here that the atmospheric light $\boldsymbol{A}$ is constant for all the frames contained in the above short time period. By subtracting Eq. (4) from Eq. (5), the equation of temporal update from $\hat{t}_k$ to $\hat{t}_{k+1}$ is obtained as follows:

$$\hat{\boldsymbol{\tau}}_{k+1}(x,y) = \hat{\boldsymbol{\tau}}_k(x,y) + \frac{\boldsymbol{I}_{k+1}(x,y) - \boldsymbol{I}_k(x,y)}{\boldsymbol{J}_k(x,y) - \boldsymbol{A}}, \tag{6}$$

where

$$\hat{\boldsymbol{\tau}}_k(x,y) = \begin{pmatrix}\hat{t}_k(x,y)\\ \hat{t}_k(x,y)\\ \hat{t}_k(x,y)\end{pmatrix}, \qquad \hat{\boldsymbol{\tau}}_{k+1}(x,y) = \begin{pmatrix}\hat{t}_{k+1}(x,y)\\ \hat{t}_{k+1}(x,y)\\ \hat{t}_{k+1}(x,y)\end{pmatrix}.$$

Note that Eq. (6) is the 3-dimensional vector expression of RGB components and the division between two vectors shown in the second term of the right-hand side represents the elementwise division of each component. Using the kth transmission map vector $\hat{\boldsymbol{\tau}}_k(x,y)$, the ideal image without haze can be obtained as follows

$$\boldsymbol{J}_k(x,y) = \frac{\boldsymbol{I}_k(x,y) - \boldsymbol{A}}{\boldsymbol{\tau}_k(x,y)} + \boldsymbol{A}. \tag{7}$$

Note that this is also a vector expression and the first term on the right-hand side represents the elementwise division again. In order to update the transmission map temporally by using Eq. (6), the initial transmission map at $k = 0$ and the common atmospheric light $\boldsymbol{A}$ are required to be calculated in advance. For this reason, we applied He's algorithm only for the first frame in the proposed method to obtain initial transmission map $\boldsymbol{\tau}_0$, atmospheric light $\boldsymbol{A}$, and haze-free image $\boldsymbol{J}_0$.

IV. Experimental Results

In order to verify the proposed temporal update algorithm, we prepared three test image sequences taken by a fixed-point camera and conducted a haze removal experiments. Five samples from each test sequence are shown in Fig.1 to show the image contents. Sequence 1 consists of outdoor scene images, whereas sequence 2 and 3 indoor scene images. The outdoor scene contains typical static haze that is expected in He's method. On the other hand, the indoor scenes both contain artificial moving haze from smoke generator. The difference between sequence 2 and 3 is in their background conditions. While sequence 2 has a static background, sequence 3 contains a moving object (toy train) as a part of its background.

A. Processing Time Evaluation

The proposed method is implemented in MATLAB, and its processing time of haze removal is compared with He's method to show the expected reduction of processing time by introducing the proposed temporal update. To make a fair comparison, we implemented the common process into the same function, if possible, and used it for the performance evaluation. The computational environment of the experiment is listed in Table I. In the proposed method, Gaussian filter of $\sigma = 0.5$ is applied to each update signal that appears in the second term of the right-hand side of Eq. (6), to alleviate the accumulated noise in the transmission maps. The reason we introduce Gaussian filter instead of guided image filter is that the above update signal does not generally contain edge signals especially under the static background assumption. In the conventional method, He's algorithm is applied to each frame contained in the test sequences and the processing time accumulated for 30 frames are measured. Whereas, in the proposed method, only the first image is de-hazed using He's method, and the temporal update algorithm in section III is applied to the other 29 images.

TABLE I. Computational Environment

Programming Environment		MATLAB R2016a
PC Specification	OS	Windows10 Pro (64 bit)
	CPU	i7-6700 CPU @ 3.40GHz
	RAM	8.00GB×1

TABLE II. Computational Time for haze removal [sec]

	Conventional	Proposed	
		Filter off	Filter on
Algorithm	He's method (30 frames)	He's method (1 frame.) & Temporal update (29 frames)	
Processing Time (ratio)	48.48 (12.59)	3.85 (1.00)	4.78 (1.24)

Fig. 1 Three test image sequences captured with a fixed-point camera (960×540 pixels, 30 frames, RGB color image)

The processing time measured in the experiment is shown in Table II. In the measurement of processing time, the same program was executed 5 times and all the obtained records were averaged. It is found in Table II that the processing time of the proposed temporal update is more than 10 times faster than the conventional method, whether or not smoothing filter is applied to each updated transmission map. It is also found that the overhead of smoothing filter is not very large in processing time. This is because the processing time of Gaussian filter is relatively small, compared with the guided image filter.

B. Haze Removal Evaluation

The results of haze removal using He's method and the proposed temporal update are compared, using the three test sequences in Fig.1. All the test sequences are 1-second long, containing 30 time-series images. Samples of a restored image and its corresponding transmission map that is used in the haze removal process are shown in Fig. 2. The haze removal results (pairs of the recovered image and its corresponding transmission map) are summarized in Fig. 3. In the conventional haze removal, He's algorithm is applied to each frame repeatedly. Whereas, in the proposed method, the temporal update of transmission map with and without smoothing filter are also compared. The smoothing filter is applied for reducing the noise that typically appears in the transmission map generated with temporal update. Gaussian filter with $\sigma = 0.5$ is used in the experiments.

Test sequence 1 has a static background, and the haze is static throughout the sequence. Since the sequence well satisfies the static background assumption, the results of the temporal update is comparable to the conventional results. Test sequence 2 also has a static background, but the haze is moving from right to left. It is difficult to determine the atmospheric light $\boldsymbol{A}$ automatically for the indoor scene, we manually set $\boldsymbol{A} = (0.7, 0.7, 0.7)$ for both the conventional method and the proposed method in this experiments. Similar to the test sequence 1, it is also found that the results of the temporal update is still comparable to the conventional results. Finally, test sequence 3 is the case that does not strictly satisfy the static background assumption, because it contains a moving object (toy train) in the background. As you can see in the resulted image, the incidental image of toy train remains along its trajectory in the proposed method. Since this phenomenon could degrade the restored image significantly, it is desirable to solve this problem in future work.

C. Note on Atmospheric Light Estimation for indoor scene

As described in Section IV, He's algorithm originally estimates atmospheric light $\boldsymbol{A}$ automatically by using top 0.1 % brightest pixels in the dark channel image. The selected pixels in Test Sequence 1 and 2 are shown in Fig.3. Since He's algorithm is designed for outdoor scenes, the atmospheric light estimation works well in Test Sequence 1, an outdoor scene with static haze. The assumption of constant atmospheric light also holds correctly in this case. However, in Test Sequence 2, which is an indoor scene with moving haze, white pixels that belong to white paper on the wall and to frames of background bookshelf are selected incorrectly. Moreover, as shown in Fig.4, the estimated light changes drastically in accordance with the movement of haze (or smoke), which violates the assumption of our method and might deteriorate the haze removal result. To determine the atmospheric light automatically and improve the quality of resulted images in such situations, it is required to identify the location of moving haze and to obtain the haze color properly, which is left as a future work.

(a) Test Seq.1 (outdoor scene) (b) Test Seq. 2 (indoor scene)

Fig. 3 Top 0.1 % brightest pixels in the dark channel image

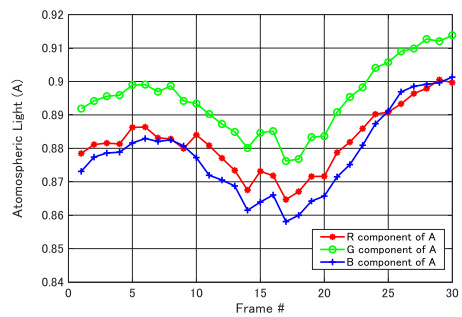

Fig. 4 Plot of estimated atmospheric light $\boldsymbol{A}$

V. Conclusions

In this paper, we proposed a fast haze removal algorithm designed for the time-series images captured by a fixed point camera. In the proposed method, the temporal difference between successive two images is utilized for updating the transmission map. It is verified through several experiments that the proposed temporal update is more than 10 times faster than the conventional transmission map generation.

However, several problems are still remaining as future work. Firstly, the haze removal result is degraded when the background contains relatively large moving objects, which should be dealt with as highest priority. Secondly, especially for the indoor scene, developing a proper way to determine the atmospheric light $\boldsymbol{A}$ automatically is required. Thirdly, the haze removal sometimes fails when the density of haze (or smoke) is unevenly distributed and/or when haze (or smoke) is moving. In the experiments in Section IV, the haze removal results from the proposed method mostly look better than the conventional one when the haze is moving (see Test Sequence 3), but the quality of haze removal should be improved further more.

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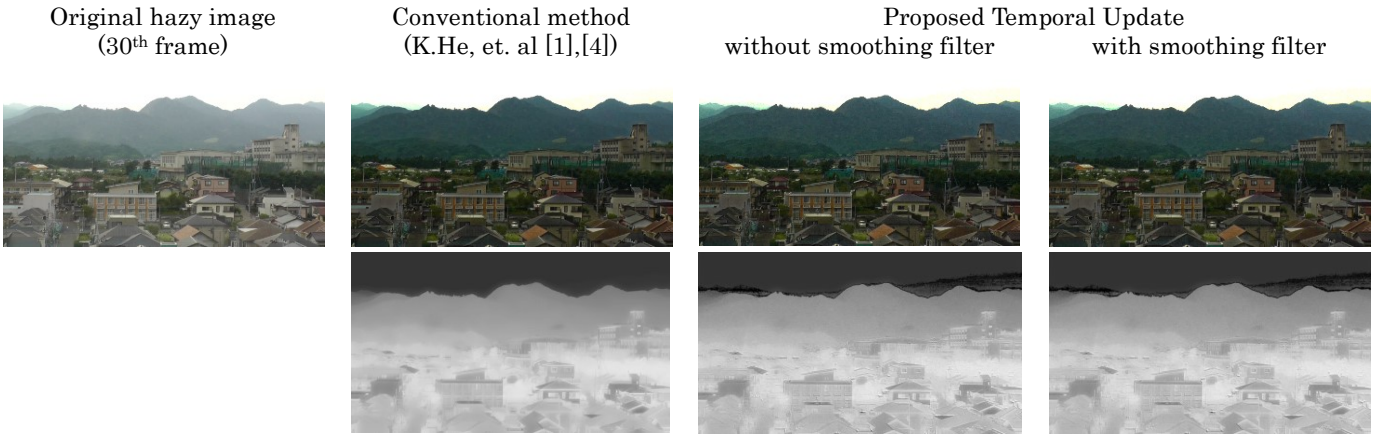
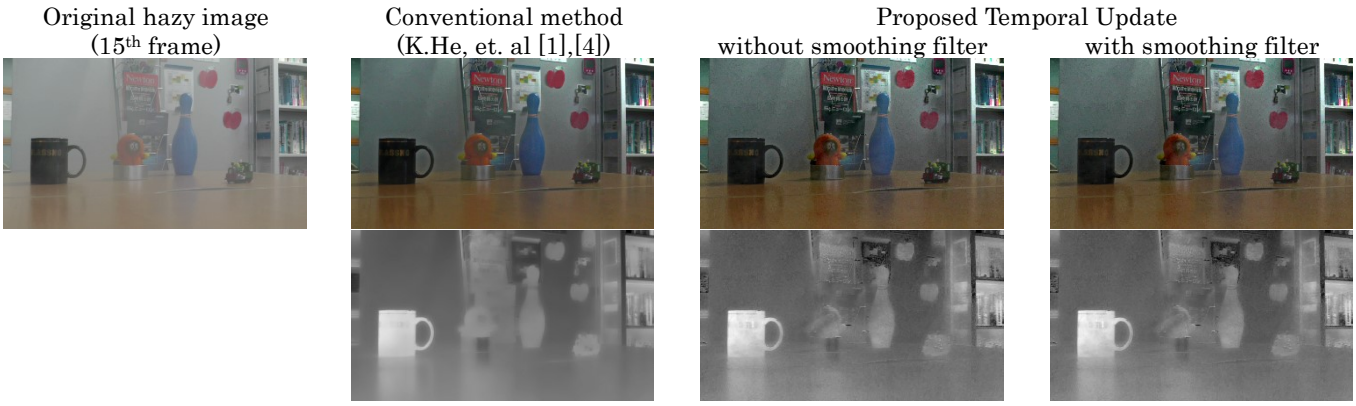
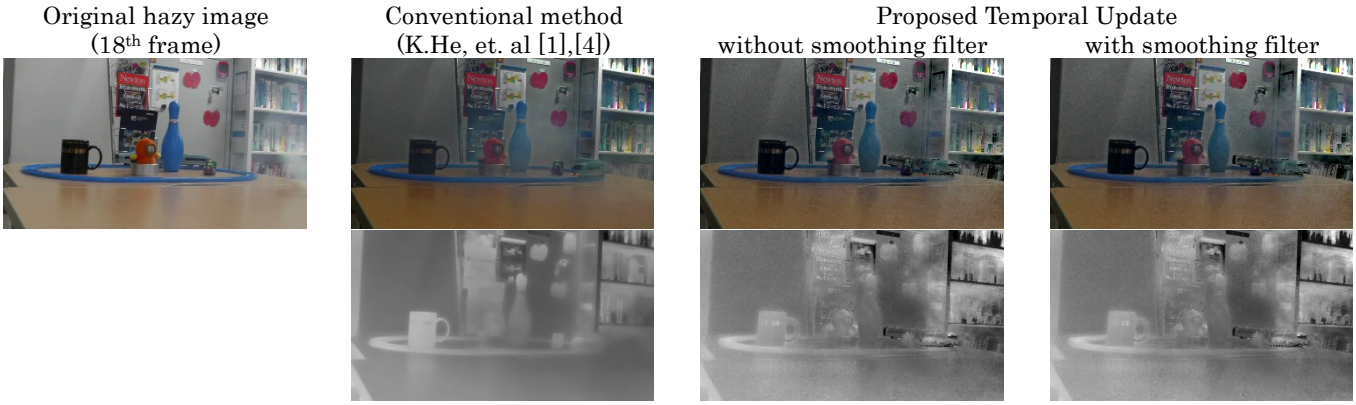


(a) Results of Haze removal: Test Sequence 1 (1st row: RGB color image, 2nd row: transmission map)



(b) Results of Haze removal: Test Sequence 2 (1st row: RGB color image, 2nd row: transmission map)



(c) Results of Haze removal: Test Sequence 3 (1st row: RGB color image, 2nd row: transmission map)

Fig. 2 Comparison of haze removal images and their corresponding transmission maps