IMAGE ENHANCEMENT OF FOG-IMPAIRED SCENES WITH VARIABLE VISIBILITY

Honghong Peng and Raghuveer Rao

Rochester Institute of Technology

ABSTRACT

Enhancement of images of foggy scenes is being investigated for application to navigational aids. Approaches based on atmospheric scatter models have previously been developed. In most cases, the assumption is made of uniform aerosol suspension leading to models of constant attenuation per unit distance. The paper addresses situations where such an assumption is not valid and proposes an approach for image enhancement when visibility varies with direction. The basis for the development of the approach is provided along with an example of application.

Index terms **–** Image enhancement, image restoration, navigation.

1. INTRODUCTION

Visibility estimation is important in various navigation applications [1]. An attendant problem of importance in developing navigational aids is the enhancement of images of scenes taken in poor visibility [2-4]. Devices that provide real-time or near real-time enhancement can be very useful in general aviation, maritime navigation and even automobile driving. Visibility limitations in the atmosphere are usually caused by light scattering suspensions (aerosol) in the air. Fog is associated with aerosol consisting of water droplets.

Methods have been proposed for image enhancement using atmospheric scatter models. Oakley and Satherly [2] and Armitage et al [3] deal with enhancing aerial images captured in low visibility using a physical model for the image intensity as a function of distance and scatter parameters. Their approach requires fitting the image data to the model through a least squares procedure. Rao and Lee [4] develop enhancement approaches based on fundamental constraints derived from the physics of ground reflectance and scatter model parameters.

A critical parameter that these approaches use or estimate is the visibility parameter β_{sc} (defined later in Eq. 1). It is typically assumed that this parameter is a constant in a given scene. However, situations where this assumption is not warranted are common. Scenes with patchy fog and variable fog density would require models allowing for β_{sc} varying in the scene. The key contribution of this paper is the development of an approach to enhance an image when we have such a situation.

2. BACKGROUND

The approach developed here is built upon the previous work in [4] which is itself based on an attenuation model. Accordingly, we summarize both the model and the prior approach in this section. Visibility degradation in the atmosphere is caused most often by light scattering. Scattering by atmospheric aerosol particles with a radius greater than approximately one tenth of the imaging wavelength is described by Mie scattering [5]. Scattering leads to an attenuation of transmitted flux, which worsens exponentially with range as

$$I_r = Ie^{-\beta_{sc} r} \tag{1}$$

where I is the reflected intensity at the surface, I_r is the irradiance at a distance *r* along the path and β_{sc} is the total volume scattering coefficient. The quantity $e^{-\beta_{sc}}$, which has a value between 0 and 1, serves as a measure of visibility.

A simplified image degradation model that prevails for most aerosols, terrain, and illumination is given as follows [2, 4]. The irradiance, $I_s(k)$, at a light sensing element *k*, such as a CCD or CMOS unit in a camera, can be modeled as

$$I_s(k) = \Omega_k I_0 \left[1 + \left(F(k) - 1\right) e^{-\beta_{sc} R(k)}\right] \tag{2}$$

where I_o is the illumination, Ω_k is the solid angle of the viewing cone at k, $F(k)$ is the reflectance of the corresponding ground patch and $R(k)$ is the distance from sensor to the patch.

Letting Ω_k be independent of k (appropriate for conventional video cameras), the image intensity $I(k)$ at pixel *k* is given by

$$I(k) = c_0[1 + (F(k) - 1)e^{-\beta_{sc} R(k)}] + n_s \tag{3}$$

where $c_0 > 0$ is a lumped constant associated with sky radiance and camera parameters (for converting irradiance I_s to pixel intensity), $F(k) \in [0,1]$ is the reflectance of ground objects impacting pixel *k*, $\beta_{sc} \in [0,\infty)$ is the scattering coefficient, $R(k) \in [0,\infty)$ is the range to ground patch corresponding to pixel *k*, and n_s is the senor noise. In daylight conditions, n_s is negligibly small and (3) may be rewritten as

$$I(k) = c_0[1 + c_1(k)e^{-\beta_{sc}R(k)}] \quad (4)$$

where $c_1(k) = F(k) - 1$. For the enhancement procedures, the distance $R(k)$ is treated as a known quantity obtainable by a measurement technique [6] or by accessing systems such as GPS-based location.

The paper's proposed approach builds upon Approach II of reference [4] which proceeds towards a solution that enhances the image by choosing a solution for which

$$\min(F(k)) = 0 \text{ and } \max(F(k)) = 1 \quad (5)$$

It establishes that solving for c_0 and β_{sc} to satisfy the constraints of (5) leads finally to

$$c_0 = \max(I(k)) \quad (6)$$

and

$$\beta_{sc} = \frac{1}{R(k)} \ln\left[\frac{1 - F(k)}{1 - I(k)/c_0}\right] \quad (7)$$

for the optimal values of c_0, β_{sc} and $F(k)$.

Thus, β_{sc} can be estimated by the following iteration algorithm after first setting c_0 to satisfy (6).

1) Initialize β_{sc}.
2) Compute

$$F(k) = \left(\frac{I(k)}{c_0} - 1\right)e^{\beta_{sc}R(k)} + 1 . \quad (8)$$

3) Let $k = k_{\min}$ where $F(k)$ has the minimum value for this iteration, that is, $F(k_{\min}) = \min(F(k))$.
4) Update β_{sc} using

$$\beta_{sc} = -\frac{1}{R(k_{\min})}\left[\ln\left(1 - \frac{I(k_{\min})}{c_0^*}\right)\right]. \quad (9)$$

5) Repeat 2) to 4) until $F(k_{\min}) = 0$.

Convergence results from the fact that the function $1 + (F_o(k) - 1)e^{-\beta_{sc}R(k)}$ is an increasing function of β_{sc} for all k for which $F_o(k) < 1$. Thus, the procedure nudges the minimum value of the reconstruction to zero at each iteration. Convergence is rapid with $\min(F(k))$ approaching close to zero typically in 3 to 4 steps.

3. NEW APPROACH

The assumption of constant β_{sc} above is not valid in many situations. It is quite common for fog density to vary with position in the scene. The basis for the new approach is provided by two observations in our experiments:

1. If the constant β_{sc} assumption holds and the approach outlined in Section 2 (which we will refer to as the "old approach") works well, the "defogged" image has a higher variance than the original "fogged" image. This should not be surprising since the enhancement uncovers hidden details and is consistent with other types of enhancement operations [7, 8].
2. Even if there is variation in fog density, the old approach yields a nominally enhanced image with improvement in certain areas of the image and no improvement or degradation elsewhere. The degradation itself takes the form of fogging in certain areas. This indicates that the value of β_{sc} obtained from the old approach is in between the maximum and minimum values of β_{sc} that would model the attenuation in different regions of the scene if it were allowed to vary.

Thus the proposed approach of this paper begins by applying the old approach first. The local variance of the resulting enhancement is compared with the local variance of the input image. The comparison is effected by taking ratios of local variances of enhanced image to that of input image. If a constant β_{sc} assumption were valid, the expectation is that this ratio would be greater than one throughout. Otherwise,

For regions where this ratio is greater than or equal to one:

$$\textit{estimated } \beta_{sc} \le \textit{true value} \quad (10)$$

For regions where ratio is less than one:

$$\textit{estimated } \beta_{sc} \ge \textit{true value} \quad (11)$$

The original image (not the enhanced one) is then partitioned into two regions, one for which the ratios are greater than or equal to one and the other for which they are less than one. The old approach is then applied to these regions separately. The process is repeated until these ratios come to a value close to one.

4. RESULTS

We illustrate application of this approach to the image of Figure 1, which shows fog covering the top portion of the scene while the bottom is clear of fog. This fog was generated synthetically using scatter models on an original clear scene. Figure 2 shows the enhanced image from the old approach while Figure 3 shows the result of applying the method of the paper after three iterations of partitioning into regions of variance ratios exceeding one and falling below one respectively. The new approach is able to defog the top region better than the old approach. Objects such as the distant hills and the cloud cover are clearly revealed. It is also seen that the old approach does enhance certain regions at the expense of others because of the actual attenuation term being variable instead of being constant. Even quantitatively, as measured from the PSNR using the original clear image, the new method yielded an image with a PSNR of 21.5 dB compared to 5.3 dB for the old approach.

5. CONCLUDING REMARKS

The paper has developed an approach for enhancing images captured in fog conditions when the fog density varies across the scene. It builds upon an earlier approach for enhancement that works for uniform fog density. The work has been motivated by applications to navigational aids. To this end, we have observed the approach to converge fast enough for eventual incorporation in a real-time system. Currently, results have been obtained through experiments with fogs generated in scene simulators. Work is under way to assess performance in real scenes.

Acknowledgment: This work was made possible by a grants from the NYSTAR CAT/CEIS Center in Rochester, New York in conjunction with ITT Corporation's Space Systems Division.

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Figure 0. Fogged scene with variable β_{sc}

Figure 2. Enhancement with old approach

Figure 3. Enhancement with paper's approach