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Mitigation of Atmospheric Contrast Degradation via Image Enhancement

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Abstract – Images obtained in bad weather such as haze, fog may have low contrast, particularly towards the top of the image. The technical challenge is to reverse this process – provided with just the "foggy" scene, estimate the contribution due to optical scattering and so recover the original scene. This is possible for a general flat-field scene and a forward-looking camera, although there are some limitations due to noise effects.

Keywords – Imaging, image enhancement, optical scattering

I. INTRODUCTION

Images obtained in bad weather such as haze, fog and mist are degraded by aerosols suspended in the atmosphere and may have low contrast, particularly towards the top of the image. Under clear conditions, the only light entering a camera is that directly reflected by objects in the field of view. If haze, fog, drizzle, rain or light smoke is present then some of the light originating from the primary light source (normally the sun, but could also be an artificial light source) is scattered so that it enters the camera. This is known as the “airlight”. The resultant image seen by the camera is essentially the sum of the original unaffected scene image and the image of the airlight. The intensity of the airlight at any point in the image is a function of:

1. size and composition of scattering particles
2. concentration of particles
3. scene-camera range
4. illumination distribution

All these parameters are subject to change – some over the image area, and some over time. The amount of scattering is also dependent on the wavelength of the light (e.g., greater for blue than red wavelengths). The degradation increases exponentially with the distance from the scene to the image sensor. This results in non-uniform attenuation of different optical wavelengths at the same distance and so colour distortion occurs. Light from the sky is also diffused by the aerosol in every direction. The irradiance from this diffused light also increases with the distance. The combined effect of these scattering phenomena is to reduce image contrast.

II. BACKGROUND

There is a common belief that a dispersive medium such as fog scatters the light originating from the scene itself and so blurring the image to such an extent that original image recovery is very difficult (if not impossible). The simple simulation of a “foggy” scene shown in Figure 1 below suggests that this is not the case.

The image in figure 1(b) is generated by transforming the image in figure 1(a) according to a range-dependent atmospheric model [1] that represents a forward-looking view. The contrast loss at the top of the image is greater than that at the bottom. The resultant is a characteristic foggy scene with the background obscured and all colours
appearing washed out. The technical challenge is to reverse this process – provided with just the “foggy” scene, estimate the contribution due to optical scattering and so recover the original scene, as shown in figure 1(c). This process has been described as “de-weathering” in the literature [2]. In practice one undesirable effect of image enhancement is to reduce the PSNR. For example the PSNR in figure 1(c) (middle part) has been reduced from 44dB in figure 1(b) to 24dB. However the gain in perceived image quality is still very high.

III. METHODOLOGY

Mitigation of this type of atmospheric degradation can be effected in various ways. The best-known image enhancement tools are based on histogram equalisation. Most of these programs will provide some improvement in image quality when applied to atmosphere-degraded images. However the best results are obtained when specific algorithms are used that take account of the specific nature of atmospheric degradation [1]-[6]. Such algorithms are idempotent in the sense that they correct a specific defect in the image. If no atmospheric degradation is present then they will introduce no changes in the image. Since the atmospheric degradation is, in general, wavelength-dependent, the enhancement is best implemented in RGB colour space. The required enhancement operation is expressed as a straight-line transformation between an input RGB pixel \((x_r, x_g, x_b)\) and an output pixel \((y_r, y_g, y_b)\) such that:

\[
\begin{align*}
  y_r &= m_r \left( x_r - c_r \right) \\
  y_g &= m_g \left( x_g - c_g \right) \\
  y_b &= m_b \left( x_b - c_b \right)
\end{align*}
\]

where \(m_r, m_g, m_b, c_r, c_g, \) and \(c_b\) represent gain and offset parameters. The required gain and offset parameters may vary for different parts of the image since the extent of the degradation will depend on range.

In general some kind of model is needed for the way in which the range changes in different parts of the image [4]. This paper considers the “flat-field” model in which the scene is considered to be approximately planar and viewed from a forward-looking camera at some height above the plane.

The distance between the camera and the terrain varies in dependence upon position within the image plane, as shown in figure 2. This position is represented by a variable \(v\) which takes a value of 0.5 at one extreme, -0.5 at another extreme and 0 at the centre. The degree of range variation in this case can be described by a single parameter, \(H\), that ranges from 0 to 2.0.

\[
H = \frac{\text{FOV}}{\theta},
\]

where \(\theta\) is the look-down angle and FOV is the field-of-view.

\[
R \approx R_0 \frac{1}{1 - Hv}, \quad (3)
\]

where \(R_0\) is the range at the centre of the image. If \(H\) is small then this corresponds to a narrow-field camera looking straight down from above onto the scene. In this case the atmospheric degradation is stationary throughout the scene, leading to simple contrast loss [3]. When \(H\) approaches 2.0 this corresponds to a forward-looking camera capturing a scene in which the range at the top of the image is nearly infinite (for example up to the horizon). In this case the degradation is highly non-stationary, with very low contrast in the upper parts of the image. The example shown in figure 1(b) corresponds to \(H=1.0\) and a mid-image contrast of 0.1; if there are dark objects or markers in the scene then the detection of atmospheric contrast loss is relatively simple. In the case when there are no dark objects in the scene a special statistical analysis can be used to detect simple contrast loss [3] providing the image texture matches certain assumptions.

Since the airlight depends on range and the range depends on the vertical image coordinate \(v\), the image offsets, \(c_r, c_g, \) and \(c_b\) in (1) must be computed separately for each image line. The level of airlight is governed by the Volume Total Scattering Coefficient (VTSC) \(\beta\) and the sky spectral radiance \(C\). For example, the “red” offset \(c_r\) and scaling factor \(m_r\) are given by [1]:

![Figure 2. Scene geometry](image-url)
where $C_r$ and $\beta_r$ are weighted averages of the spectral radiance and VTSC in the red channel respectively. The absolute value of $R_0$ is difficult to estimate and is not important in this application; rather it is the product of $\beta$ and $R_0$ that determines the required transformation (1). A total of seven constants must therefore be estimated in order to enhance a degraded colour image, the three spectral radiance values ($C_r$, $C_g$ and $C_b$), three scaled VTSC values ($R_0\beta_r$, $R_0\beta_g$ and $R_0\beta_b$) and a geometry factor $H$. The simplest way to estimate the spectral radiance values is to take the value of the brightest pixel in the corresponding colour channel. This leaves only four parameters to be estimated. This may be achieved using a combination of the techniques described in [1] and [3].

With an appropriate architecture, such enhancement can be applied to a high-definition video stream in real-time [5][6]. Since the actual video processing is very simple, i.e. subtraction and scaling according to (1), it is advantageous to separate the relatively complicated statistical analysis algorithm from the video processing pipeline. In this way very low latency (in the order of nanoseconds) can be achieved. The processing architecture of a current commercial system [7] is shown in figure 3 below.

Conventional video sources are gamma-encoded and this non-linear transformation must be reversed prior to processing. A transformation from YUV to RGB encoding is also required prior to processing. Although the video process operated at full video rates (25 fps for PAL and 30 fps for NTSC), only a subset of frames, typically one in four, are used for airlight analysis. The reason for this is that the pattern of atmospheric degradation changes relatively slowly. The enhancement coefficients are held in high-speed memory for use in the enhancement transformation (1). The video pipeline is implemented using a TI DM642 DSP processor and the image analysis is implemented using an Intel 8086 Core Two Duo processor.

### IV. RESULTS

An example of this type of enhancement is shown in figure 4 below.

The image shown in figure 4(a) was taken from an aircraft in light rain conditions and recorded using Beta-SP tape prior to digital frame capture. This image was analysed using the proposed technique; the estimated value of $H$ is 0.41 and the scaled VTSC values are 0.48, 0.51 and 0.48 for
the red, green and blue channels respectively. The corresponding airlight component is shown in figure 4(b). The enhanced image using (1) is shown in figure 4(c). As expected the PSNR is reduced as a consequence of the enhancement process by approximately -6 dB the top of the image and -3 dB at the bottom.

The idempotent property is illustrated by figure 5 below. Here two images, shown in figures 5(a) and 5(c), with similar scene content but different levels of atmospheric degradation are processed. The results are shown in figures 5(b) and 5(d). The image in 5(b) is hardly changed when compared with the input shown in figure 5(a). However the image shown in figure 5(d) is considerably changed from the input shown in figure 5(c).

![Original –clear](image1.png) ![Enhanced](image2.png)

(a) Original –clear  (b) Enhanced

![Original –foggy](image3.png) ![Enhanced](image4.png)

(c) Original –foggy (d) Enhanced

Figure 5. Illustration of idempotency

V. DISCUSSION

The main limiting factor is the noise present in the image. In general this is due to a combination of sensor noise and transmission/recording noise.

The dominant sensor noise is usually shot noise. A typical image sensor might have a Quantum Well Depth of 50,000 electron-hole pairs. This gives a Peak Signal to Noise Ratio (PSNR) of:

\[
PSNR = \sqrt{QWD} = 224 = 47 \text{db}
\]  \hspace{1cm} (5)

This is the maximum PSNR that is achievable. In practice there are other noise sources that will reduce further the PSNR. In particular, lossy encoding processes such as H264 introduce additional noise that can be a problem in this application. The most important challenge for the future is to embed this type of processing within a camera unit. This will give important benefits, in particular the ability to apply the enhancement to the raw image data before any lossy processing is introduced by downstream encoders. The main difficulty is that the current fog analysis algorithm makes use of floating-point arithmetic that is relatively costly to implement. Once the algorithm can be expressed in fixed-point form then implementation via DSP technology will be straightforward.

VI. REFERENCES


