Restoration of Turbulence-Degraded Images Using Pixel Histograms

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Abstract: The most-common method of restoration of turbulence-degraded images restores the sharp edges of an image but makes them jagged. We raise the pixel histograms to a certain order, which creates sharp but straight edges.

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1. Introduction

The two most noticeable distortions caused by atmospheric turbulence are the displacement and the spreading (blurring) of the irradiance in the image plane. The displacement is when the irradiance that would arrive at a certain point in the image plane if there were no turbulence actually arrives at a certain distance away from it. The spreading (or blurring) is when the irradiance that would arrive at a certain point is actually spread out around that point. For a wide field-of-view imaged over a long horizontal path in the surface layer, these effects vary over space and time and cause straight edges to appear wavy with variable blur. An example of this can be seen in part (a) of Fig 1. The image was taken using a high-speed digital visible camera with a 1.4 m focal length telescope having a 10 cm aperture. It used exposure time of 4 ms, at a rate of 250 fps and over a period of 8 s. The target is a black and white panel 3 m wide by 1.5 m high located 1 km away. The sequence of images was taken as part of a land trial organized by the NATO group SET-072/RTG-40 on Modeling Active Imaging Sensors. The trial took place at the High Energy Laser Systems Test Facility at White Sands Missile Range, NM, 14-18 November 2005.

Part (b) of Fig 1 shows the average image over the entire sequence. We notice that although the edges are straight, they are also quite blurry. This is due to the blurring of the individual images, but also to the displacements which create as an additional blur in the average image. To eliminate blurring, Glick *et al.* [1] proposed the use of the most-common (or modal) gray level value for each pixel. In other words, over the image sequence, each pixel will take on a range of gray level values a certain number of times. We can thus attribute a histogram of values for each pixel. We can also find the 'modal' (most frequent) value for each pixel and form the modal image, shown in part (c) of Fig 1. We justify this procedure by assuming that the most probable value of the turbulent index of refraction's fluctuation is zero. If true, this would imply that the most probable image in a very long sequence should be the undistorted image. It therefore follows that the modal value for a given pixel would be close to its true value, and that it is also easier to estimate for a limited sequence of images.

Part (c) of Fig 1 displays sharper edges than for part (b), but it also shows edges that are rough or jagged. This could be a problem if one needs to use derivatives, such as the gradient, of the restored image. In the next section, we introduce a method that yields some of the sharpness of the modal image while inhibiting rough and jagged edges.

2. Variable order probabilities

Any given pixel in the image can have a discrete and finite set of gray values, denoted by the index $0 \leq i \leq L$. Over the sequence, each gray value occurs n_i times, defining a histogram for that pixel. From this, we define the following probability distribution of order α.

$$p_i^\alpha = \frac{n_i^\alpha}{\sum_{i=0}^{L} n_i^\alpha} \qquad (1)$$

We can use Eq (1) to define an average gray value of order α. It is clear that the first-order average is simply the average as commonly understood. However, as we increase the order, the modal peak becomes more and more prominent and the rest of the distribution tends to be attenuated (as shown in Figs 2 and 3). Thus, as the order tends to infinity, the corresponding probability distribution will become ever more peaked about the mode such that it's the corresponding average will tend towards the mode. By setting the order at a reasonable value, say $\alpha = 3$, we obtain a compromise image (part (d) of Fig 1), between the average and the mode, that is reasonably sharp without being overly jagged or rough.

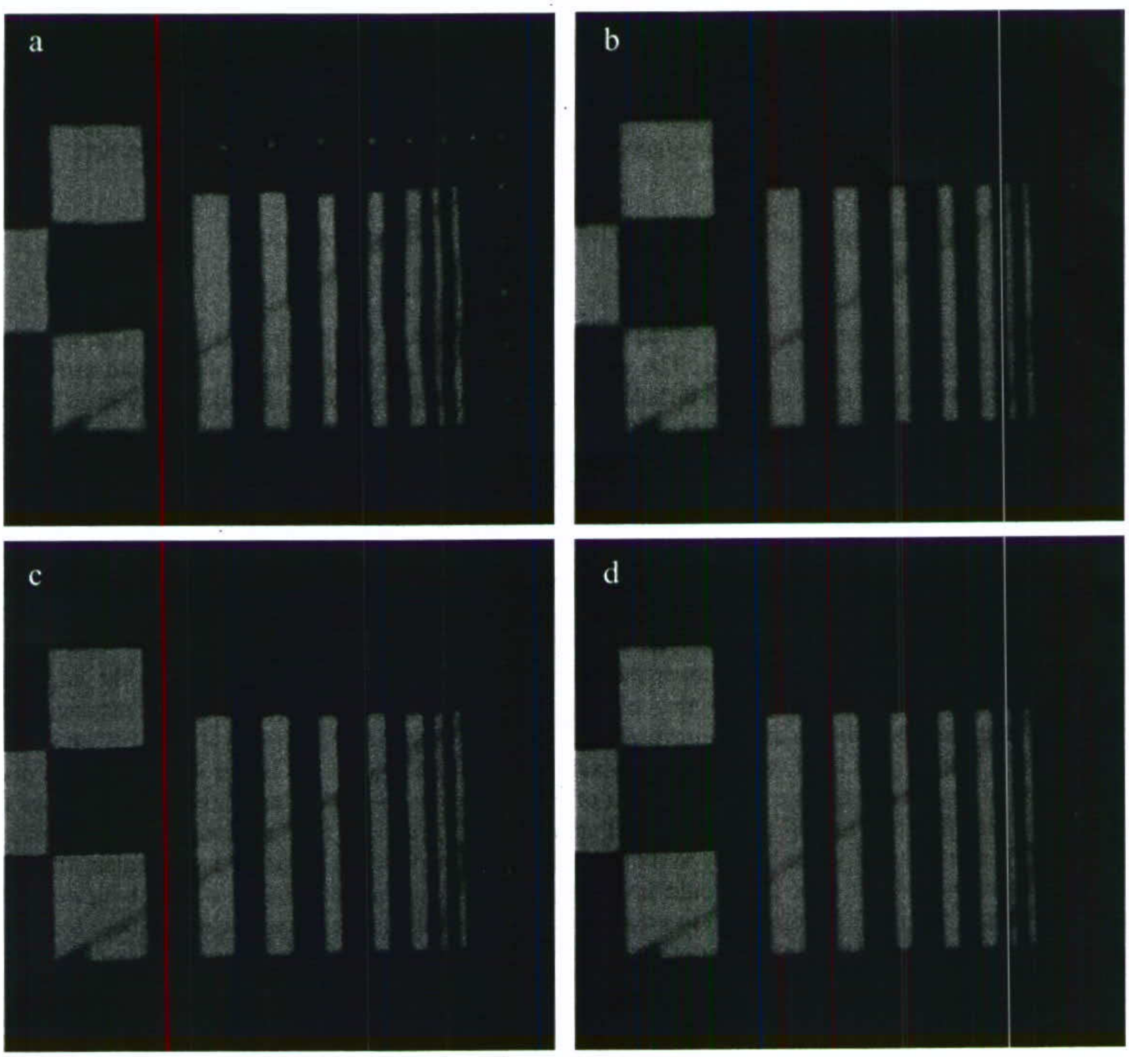

Fig. 1. A sample image from a turbulence-degraded sequence of images (a), the average image from that sequence (b), the modal image (c), and the third-order average (d).

Figure 2 demonstrates the rather complex relationship between the average, the mode and the higher-order averages defined by Eq (1). It shows the first-order ($\alpha = 1$) probability distribution of a pixel in the middle of a horizontal edge (thick gray curve). It has one modal peak at 122 (denoted by the vertical dotted line), but also a few other peaks that compete with the modal peak when we pass on to the third-order probability distribution (thin black curve). The third order shows better defined peaks with the modal peak still at 122 but a strong competing peak around 75. Because of this, the third-order average (vertical black dashed line) is further from the mode than the first-order average (vertical gray dashed line). This is contrary to the expectation that the higher-order averages should move progressively towards the mode as the order increases, which is shown in Fig 3. There we see the first-order probability distribution (thick grey curve) of a pixel on the same horizontal edge but slightly closer to the bright area. The probability distribution is skewed with one main lobe. These features are accentuated as we go to the third-order probability distribution which causes the third-order average to move towards the mode.

3. Conclusions

We have developed a method for obtaining images that combine the sharpness of the modal image with the smoothness of the average image. This is done by creating a higher-order probability distribution from the histogram of the gray values for each pixel, then obtaining a higher-order average gray value for each pixel. As the order increases, the higher-order average image should normally approach the modal image. However, we have seen that this can be a complicated and non-linear process that depends on the form of the pixel's histogram. Nevertheless, we believe that we have presented a promising restoration method for turbulence-degraded images.

4. References

[1] Y. Glick, A. Baram, H. M. Loebenstein, and Z. Azar, "Restoration of turbulence-degraded images by the most-common method," Appl. Opt. **30,** 3924-3929 (1991).

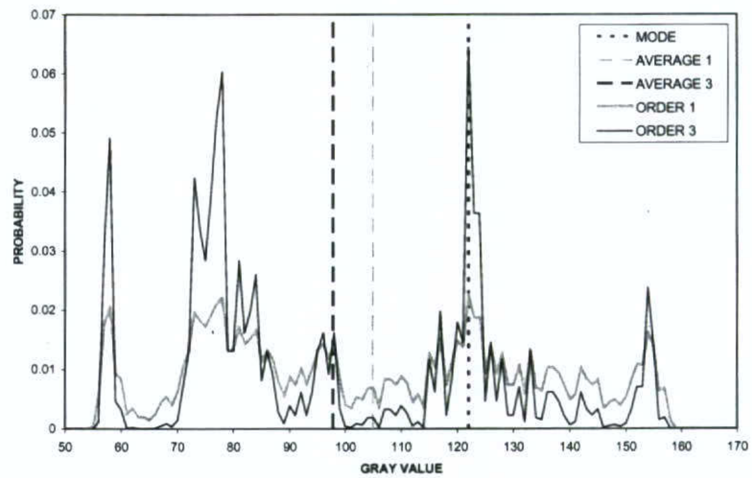

Fig. 2. The probability distribution of a pixel in the middle of a horizontal edge (thick gray curve), the third-order probability distribution (thin black curve) along with the modal value (vertical dotted line), the first-order average value (vertical dashed gray line) and the third-order average value (vertical dashed black line).

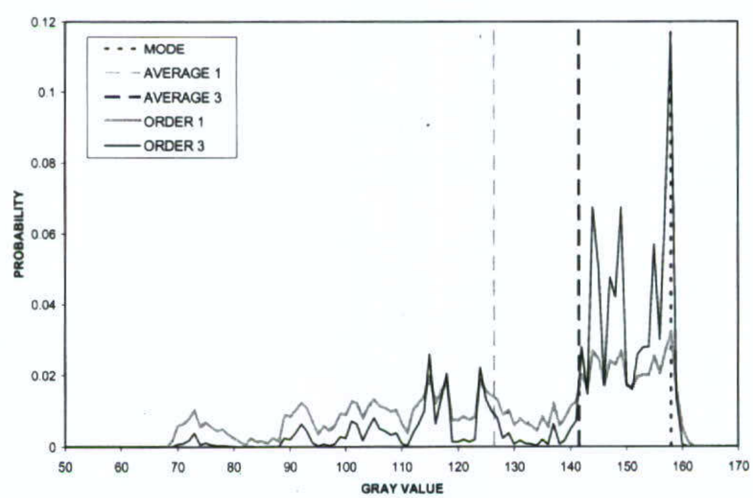

Fig. 3. The same as Fig 2, but for a pixel that is further into the bright region from the horizontal edge.