Elimination of distortions on images in the existence of turbulence

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Abstract. The aim of the study is to eliminate the influence of the turbulence model on the photographed images. This problem is solved by computer processing of images containing such distortions. In the course of the work, images with simulated turbulent distortions were obtained, and they were also post-processed using cascade filters.

1. Introduction

The problem of turbulence is quite common in everyday scientific life. Often, when conducting field experiments, a photo or video is taken. The environment surrounding the object under study has heterogeneities in the refractive index, which leads to a distortion of the results obtained. In normal photography, this is noticeable in the quality of the recorded picture. Suppose you make an experiment on photofixation and the subsequent digitization of a car license plate located at a considerable distance from the camera. In the presence of moderate or severe turbulence, distortion will occur, resembling a blurring. Due to this distortion, it may happen that a car license plate cannot be recognized, which is applicable to the digitization task inevitably leads to an error. When visualizing through the atmosphere, in addition to defocusing, a distortion of the geometry of the observed object may also occur. This well shows that the elimination of the influence of turbulence is a fairly promising direction for research [1]. The methods of turbulence research are the Background Oriented Schlieren method, Particle Image Velocimetry (PIV) method, Particle Trace Velocimetry (PTV) method, and others. Each method has its limitations. So, the Background Oriented Schlieren method is essentially integral, and with the help of it information about the volume containing heterogeneity is obtained. PIV and PTV methods allow to obtain information in the cross section of the volume, but the experimental setups are more expensive and more complex in their implementation [2-5].

Elimination of image distortions is carried out by computer filtering. In the case of elimination of a certain type of distortion, there is often a model of this distortion, which allows us to solve the inverse problem and determine the parameters of the necessary filtering. Currently, a lot of work is being done on modeling turbulent flows using numerical simulation methods, but such calculations are usually approximate or require large computational power. Such simulations make it possible to understand what the distribution of the air flow velocity or pressure will be in a particular object under study, for example, in a turbine [6-9]. In the general case, when the distortion model is not known or the reverse solution is not found, sometimes you can use the basic filtering operations in order to achieve image enhancement.
2. Modeling of distortions and filtering of distorted images

One of the variants of modeling the distortions introduced by turbulence on images obtained from a camera while photographing is presented below. The distortion model in [10] is based on the consideration of the turbulent properties of the atmosphere. This model is presented below:

\[ H(u, v) = \exp(-k \cdot (u^2 + v^2)^{5/6}), \]

where the coefficient \( k \) describes the turbulent properties of the atmosphere. So, at \( k = 0.001 \) there will be moderate turbulence, and at \( k = 0.00025 \) it will be weak. Up to a factor of \( 5/6 \) in the exponent, this expression coincides in its form with a Gaussian low-frequency filter [11].

To simulate the distortion, an algorithm was implemented by software that performs convolution of the original image with a filter. Figure 1 shows the distortion with different used coefficient of the turbulent atmosphere.

![Simulation of turbulent distortion in images](image_url)

**Figure 1.** Simulation of turbulent distortion in images: (a) \(-k = 0\); (b) \(-k = 0.0001\); (c) \(-k = 0.0002\); (d) \(-k = 0.0003\).
The distorted images were shifted 5 pixels to the right in order to determine the relative error at different turbulence coefficients. Then the relative error \( \delta \) can be defined as the ratio of the difference between the theoretical and experimental shift to the theoretical shift. The experimental shift was determined using the PivView 1.7 Demo program. This program performs correlation processing of images. For a pair of images in the program, you can see not only the distribution of the correlation coefficient, but also the average displacement along the axes of the image. Two images are loaded into the program – one reference and the other with distortion. An example of downloaded images is presented in figure 2 [12-13].

![Figure 2](image)

**Figure 2.** Downloadable in the program PivView 1.7 Demo frames: (a) – reference image; (b) – Image with the parameter of introduced inhomogeneity \( k = 0.0001 \) and offset by 5 pixels.
Then, using cross-correlation processing, we construct the vector field of displacements on the images. To do this, each image is divided into survey windows with a given size, and then a cross-correlation maximum is searched for each of the survey windows. The vector field for the data in figure 2 can be seen in figure 3.

![Figure 3. Constructed vector field.](image)

The average image offset can be viewed in the “PIV” → “PIV-Statistics” menu. Here the program shows the average horizontal and vertical displacement, which is required for estimating the error. If we process a set of images with different effects of atmospheric distortion, we can construct a graph estimating the error $\delta$ depending on the coefficient $k$ (figure 8).

When an object is shot on a video camera, the influence of atmospheric distortion has its own fluctuation. A simple averaging of, say, three frames here does not help to increase the quality of the image, which will be shown below. For example, three images with simulated distortion were taken. Between themselves, the images differed in the degree of turbulence influence (coefficients $k_1 = 0.0001$; $k_2 = 0.0003$; $k_3 = 0.0005$). When calculating the average of the average image will likely get a blur, but does not improve in visual perception (figure 4). Therefore, this technique is not worth using.

![Figure 4. Averaged frame.](image)
When shooting through the atmosphere, the image of the object under study becomes blurred. This may be due both to the shaking of the camera itself or the object, or because of, for example, a strong wind in the space between the object and the camera. Given that turbulent distortions in their effects on the recorded image resemble a Gaussian low-pass filter, it is logical to assume that when filtering, use a filter that has the opposite effect [14]. For the best visual perception, an image containing the result of superimposing turbulence on a useful signal can be processed by increasing the sharpness. One way to increase the sharpness is to use a convolution of the original image with a Laplace mask. Below is a formula for image processing [15].

\[ f'(x, y) = f(x, y) - k_L \cdot z(x, y), \] (2)

where \( k_L \) is the sharpness gain (selected experimentally), \( z(x, y) \) is the convolution of the original image with the Laplace mask. This formula will be valid with a mask, the central element of which has a negative value. An example of such a mask can be a \( 3 \times 3 \) matrix with a central element equal to \(-8\), and the remaining elements equal 1. Possible variants of the Laplace mask are presented below:

\[
L_1 = \begin{bmatrix}
0 & 1 & 0 \\
1 & -4 & 1 \\
0 & 1 & 0
\end{bmatrix}, \quad
L_2 = \begin{bmatrix}
1 & 1 & 1 \\
1 & -8 & 1 \\
1 & 1 & 1
\end{bmatrix}, \quad
L_3 = \begin{bmatrix}
2 & -1 & 2 \\
-1 & -4 & -1 \\
2 & -1 & 2
\end{bmatrix}.
\]

For example, an image with a simulated distortion of \( k = 0.0002 \) was taken. In figure 5 you can see the result of the increased sharpness. During processing, we must not forget that as a result of filtering, the brightness values of pixels may change in such a way that they go beyond the original brightness range of pixels (for example, in the MathCAD program, the brightness varies from 0 to 255). In this case, it is worthwhile to further optimize the image – that is, to maintain its dynamic range.

![Figure 5. Result of sharpening: (a) – the original image; (b) – processed image.](image_url)
Figure 6. Image Processing Results: (a) – source image with $k = 0.0002$; (b) – contrast enhancement; (c) – sharpening and contrast enhancement.

Figure 7. Image Processing Result: (a) – source image with $k = 0.0006$; (b) – processed image.
However, this algorithm is far from universal – it is suitable only for images with a low influence of turbulence. Figure 7 shows the result of processing in the case of a stronger distortion ($k = 0.0006$). It is clearly seen that when processing minor distortions intensified, which was to be expected.

For the processed images, an error estimate was also made (figure 8), which showed that the cascade of filters used in the case of small turbulence actually improves the image.

![Figure 7](image)

**Figure 7.** The result of processing in the case of a stronger distortion ($k = 0.0006$).

![Figure 8](image)

**Figure 8.** Error estimate.

3. **Conclusion**
According to the results of processing, it can be said that the selected algorithm is suitable only for distortions corresponding to weak turbulence. When processing it is worth paying attention to the noise of the original image, because if you use sharpening, then in the presence of noise they will also stand out. To eliminate the effects of stronger turbulence in images, it is still worth solving the inverse task when using the distortion model.

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