Synthesized digital images of aerosol plumes

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Received February 9, 2000

The possibility of applying digitally generated images of aerosol plumes to measuring the power of a point source of pollution with preset parameters is considered. The methods used in processing and analysis of dynamic images of the aerosol plumes is presented. The outcomes of the image analysis of telephotometric monitoring of aerosol plumes distribution in the atmosphere are discussed.

Introduction

Different optical systems for remote sensing can be used for performing an operative monitoring of the state of the atmosphere over industrial zones, including passive means based on recording solar radiation scattered by the objects under study. The observations can be carried out both in the IR (thermovision systems) and visible wavelength ranges (TV systems).[1,2]

It is common for passive methods, that the brightness contrast of an object is measured by one or another technique. For example, in the Ringelmann method the brightness of a smoke plume is visually estimated by an operator against a contrast background by use of special test-patterns that are widely used at the stations for environmental monitoring.

Such parameters of the smoke plume from a stationary source, as illumination, distribution of the number density, optical properties of particles, state of the atmosphere and inhomogeneity of the background affect the formation of the initial image. A telephotometric technique for control of the intensity of a stationary source with the known parameters is developed at present time.[3] In this method the TV records of the process of propagation of the aerosol plume, subsequent statistical processing and analysis of the digital videodata are carried out in order to determine the source intensity from the distribution of the brightness contrast of an object over the field in the video image.

1. Experimental setup

Experimental setup for digitizing the video signal was created on the basis of MMX166 personal computer (Fig. 1). The setup consisted of an ordinary VHS Panasonic M7 video camera and OLYMPUS 440C digital camera *1*, S3 ViRDGE PCI video adapter with a TV-tuner *2*, Intel MMX166 multimedia microprocessor *3*, and input–output device (*4*, *5*). The analog video signal from the video camera came to the 96-bit analog-to-digital converter of the video adapter, and then the digital sequence was recorded in the AVI format to the hard disk. The frame rate cloud be selected from 1 to 15 frames/s at the size of a 16-bit image of 320×240 pixels (that corresponds to the VHS standard). The standard software provided by the firm-producer of the video adapter was used to enter the video data into the computer. The software was linked to the serial port of the computer. After recording the video signal (or pictures) to the computer, the initial AVI file containing the video sequence was divided into separate graphic files of PIC format, i.e., the frames of the initial video sequence. Then the images were converted to the 8-bit ones (with 256 gradations of grayness) and then the signal was processed and analyzed. Processing and analysis of the digital video data (or digital images) were carried out using the original algorithms and software developed in the frameworks of this research project.

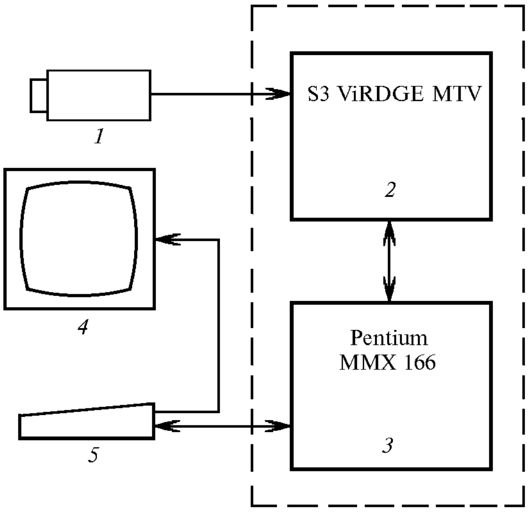

Fig. 1. Block diagram of the experimental setup.

2. Statistical processing of video images of the aerosol plumes

The process of aerosol plume dispersal from the stationary source in the turbulent atmosphere is a random dynamic process. So it is necessary to consider the digital video images as digital dynamic images (dynamic fields) and therefore to apply the statistical methods for processing and analysis of the images.

The dynamic image was considered to be a time sequence of 2D or 3D images $f(x, y, t)$ or $f(x, y, z, t)$ representing the dynamics of some process.[4] It was supposed that the subsequent frames were recorded in time intervals differentially small as compared with the characteristic time constant of the dynamic system. This means that the subsequent frames correlate in time to a sufficient degree that differs the dynamic images from an arbitrary set of frames. The correlation between separate frames of the video sequence depends on the speed of particle transport and is high during quite long time intervals as compared with the time interval τ between the adjacent frames in the initial video sequence (at a usual rate of digitizing $\tau = 1 - 1/30$ s). It was revealed that the value of the time interval τ' during which the correlation coefficient decreases down to 0.95 is 1.5–1.9 s at the wind speed of 8–10 m/s, and $\tau' = 3$–3.5 s at a weak wind (0.5–1 m/s).[5]

The digital sequences were constructed from the synthesized images of aerosol plumes based on the calculations performed. Each frame of such a sequence is the result of averaging the frames of the initial video sequence over the time interval τ':

$$I(x_i, y_j, t_m) = \frac{1}{n} \sum_{k=1}^{n} I'(x_i, y_j, t_k),$$

where $I(x_i, y_j, t_m)$ is the element of a synthesized image of the sequence, $I'(x_i, y_j, t_k)$ is the element of the image of the initial sequence; $n = \tau'/v$, v is the frame rate in the initial video sequence, x_i, y_j are the coordinates of the element. The dynamic synthesized image of the aerosol plume obtained in such a way bears information about the time variation field of brightness contrast of the aerosol plume.

Summing the frames of the initial sequence yields statistical accumulation of data on the object during the time interval τ'. It was also revealed that the correlation coefficient between the synthesized images in the sequence is no less than 0.96. Thus, the sequence of the synthesized images is also the dynamic image.

The synthesized dynamic images of aerosol plumes have some advantages as compared with the initial ones. First, constructing of the synthesized images leads to suppression of the additive noise (pulsed and digitization noise), amplification of the signal and extension of the dynamic range.[6,7] Second, the synthesized images bear statistical information about the object, i.e., this is a sort of statistical processing. Third, representation of the digital video record in such a form is quite effective way of compressing video data. If, for example, the record rate is 25 frame/s, and the time interval $\tau' = 2$ s, the synthesized dynamic image occupies 50 times less memory than the initial video sequence.

Another way of preliminary statistical processing is representation of the initial data in the form of a synthesized image obtained by means of time averaging the brightness over all frames of the video sequence and over the entire period of measurements:

$$I(x_i, y_j) = \frac{1}{n} \sum_{k=1}^{n} I'(x_i, y_j, t_k),$$

where $I(x_i, y_j)$ are the elements of the synthesized image, $I'(x_i, y_j, t_k)$ are the elements of the initial video sequence, x_i and y_j are the coordinates of the elements, $n = T/v$, T is the observation time, v is the frame rate in the video sequence. This operation is equivalent to the operation of integration of a video signal over time.

The synthesized image of the aerosol plume obtained in such a way is the spatiotemporal distribution of brightness contrast field of the aerosol plume. In addition to the above-mentioned factors, such characteristics as time stability of the particle transfer direction and temporal fluctuations of vertical and horizontal components of the wind velocity affect the formation of the synthesized image of the aerosol plume. If the wind direction has been constant and the plume has a well pronounced direction in time, the smoke plume is well seen in the synthesized image. In contrast, if the image of the smoke plume becomes strongly diffuse, smeared by temporal fluctuations of the particle transfer velocity, the synthesized image bears extremely low information and does not suit the subsequent analysis. Temporal fluctuations of the vertical and horizontal components of the wind velocity change the initial image so that the maximum of the brightness contrast is displaced in the synthesized image to the aerosol source. This fact is essential for analysis of images of the aerosol plumes. Typical conditions under which smog appears are one of the particular cases when the synthesized images can be used.

The process of plume dispersal was recorded by means of a video camera supplied with a built-in AGC (automatic gain control) function, due to which the dynamic range of the signal was automatically tuned to the object and the image contrast was changed. In particular, one can calibrate the video camera by means of inserting standard objects (for example, the test–objects of TON–1 type) into the image field and fixation of the brightness and the image contrast.

Thus, preliminary processing of the digital images of aerosol plumes was carried out in a few stages: 1) correction and normalization of the initial images; 2) construction of the synthesized dynamic images; 3) construction of the synthesized images based on the synthesized dynamic images.

3. Analysis of video images of the aerosol plumes

Traditionally, image processing means preliminary processing, i.e., processing yielding a new image. The term “image analysis” is not preconceived now.[6] According to literature data, the term “image analysis” has triple meaning: 1) classification and recognition of images; 2) measurement of different quantitative data; 3) meaning of the problem of understanding images. In this paper "image analysis" is considered as the second of the aforementioned meanings.

Statistical analysis of the recorded dynamic images that underwent preliminary processing was carried out in order to determine the brightness contrast of aerosol plumes and to find the power of emissions of the sources of pollution. The power of aerosol source M can be defined as the number of matrices N transferred through the zx plane perpendicular to the wind direction in unit time. The power of emission is related to the concentration by the following relationship:

$$M = V_y \iint\limits_{-\infty}^{\infty} \mathrm{d}z\mathrm{d}x\ \rho(x, y, z, t),$$

where V_y is the wind velocity component along the direction of the aerosol plume propagation y; $\rho(x, y, z, t)$ is the concentration of particles.[8] Distribution of the concentration together with the optical properties of particles and illumination causes the intensity distribution I of light scattered by the aerosol plume. If the conditions of illumination of the object and particle parameters are fixed, the intensity of light scattered by the aerosol plume is proportional to the plume power:

$$\iint I(x, y, z, t)\ \mathrm{d}z\mathrm{d}x \sim M.$$

The aerosol plume brightness in the selected area of measurements is determined from the threshold value of the brightness of the background against which the plume dispersal is observed. As follows from analysis of video data of the laboratory experiments on simulation of the process of the aerosol plume dispersal,[8] to determine the absolute value of the aerosol emission power, one can use the following values:

1) mean brightness of the aerosol plume $<I(t_m) - I_f(t_m)>$ normalized to the background:

$$<I(t_m) - I_f(t_m)> = \frac{1}{N} \sum_{i=1}^{n} \sum_{j=1}^{k} \left| I(x_i, y_j, t_m) - I_f(t_m) \right|,$$

where $I(x_i, y_j, t_m)$ is the element of the frame t_m; $I_f(t_m)$ is the background brightness value; $n \times k$ is the size of the area of averaging; $N = n \times k$;

2) maximum brightness of the profile of aerosol plume image normalized to the background $<I(y, t_m) - I_f(t_m)>$:

$$<I(y, t_m) - I_f(t_m)> = \frac{1}{n} \sum_{i=1}^{n} [I(x_i, y_j, t_m) - I_f(t_m)],$$

where y is the coordinate of the image element corresponding to maximum of the intensity of radiation scattered by the aerosol particles. Calculations carried out with the images in the laboratory experiment have shown that both values are linearly related to the source power.[9] When aerosol travels in the atmosphere, the direction of particles' transport varies in time and does not remain either exactly horizontal or vertical. Difficulties appear in determination of the particle transport direction at a selected point of the plume image and in calculating the second of the above values because of a more complicated mathematical tools needed. This, in turn, increases the time of calculation. Therefore, now we use the former values for determination of the relative power of a source.

4. Results of statistical processing and analysis of telephotometric observations of aerosol emissions of the local sources into the atmosphere

In 1999 we have carried out telephotometric observations of some boiler plants of industrial enterprises and heat and power plants of the city of Barnaul. Observations were carried out under clear weather conditions and under overcast. The experiment was stated on operative observation of the following enterprises: boiler plant of the Altai Plant of Aggregates (APA), boiler plant of the Plant of Ferroconcrete Items (PFCI), and boiler plant of the "Altai Resource" enterprise. Taking video was performed under conditions of variable cloudiness, the duration of observation of each object was 20 to 25 minutes, and time interval between photographs was 10 minutes. The digital image of the PFCI boiler plant plume is shown in Fig. 2, and the synthesized image of the aerosol plume of this object is shown in Fig. 3. The variation of the mean value of the smoke plume brightness normalized to the background brightness is shown in Fig. 4. One can follow the dynamics of changes in the relative power starting from the source initiation until it reaches the steady state operation using the data on the mean normalized brightness of the dynamic images. Analyzing the dynamic synthesized images, one can obtain the information not only about the mean value of the source power during some time interval, but also to follow the dynamics of the power in time.

Fig. 2. Smoke plume of the PFCI boiler plant.

Fig. 3. Synthesized image of the smoke plume of the PFCI boiler plant.

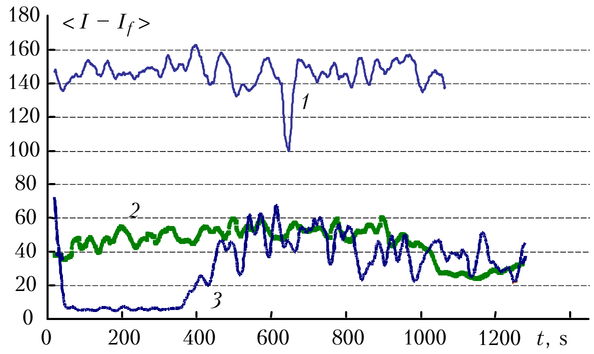

Fig. 4. Dynamics of variation of the brightness mean value of the plumes of industrial enterprises of the city of Barnaul. November 4, 1999: PFCI (*1*), APA (*2*), "Altai Resource" (*3*).

The measurement results on the brightness mean value normalized to the background are shown in Fig. 5 for synthesized and dynamic synthesized images. Differences between the values of two types of presentation of video data are caused by temporal fluctuations of the speed and direction of the particles transport.

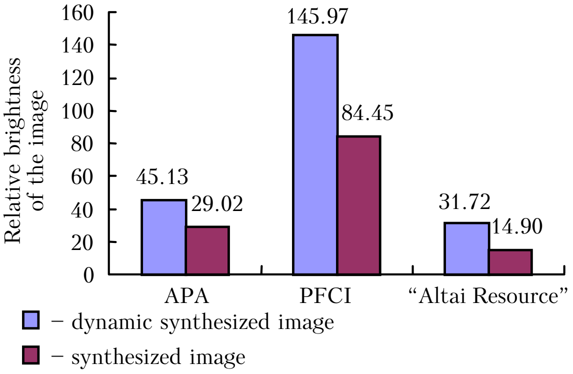

Fig. 5. Total value of the aerosol plume brightness.

It was revealed from analysis of the digital synthesized images that, in order to construct the synthesized image, it is sufficient to obtain the set of subsequent frames recorded in 1.5–2 minutes time intervals at the total duration of observations of 20–25 minutes under condition of relatively constant speed and direction of the particles transport. This fact allows one to speak about the possibility of using, for observations, the digital cameras, which has higher resolution.

However, if the transfer direction significantly changes in time, one can determine the value of brightness of the aerosol plume as well as its fluctuations in time from the initial digital frames of the videosequence (see Fig. 4). As the analysis of the results of our investigations shows, the videosequences with the frame rate 2 to 5 frames/s are optimal for construction of the dependences of such type.

Conclusion

Thus, the investigations discussed made it possible: 1) to reveal the possibility of using synthesized and dynamic synthesized images for determination of relative power of a local stationary source of pollution both at the appearance of smog in the atmosphere of industrial centers and at systematic monitoring of a local stationary source; 2) to determine parameters of statistical ensembles of images necessary for formation of the images of these types.

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