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Image Motion Compensation at Charge-coupled Device Photographing in Delay-Integration Mode

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Abstract—In this paper, a problem of image motion compensation caused by the camera motion concerning the photographed surface is considered. The camera is set on a mobile carrier, and image registration is conducted by a matrix photoreceiver on basis of charge-coupled devices (CCD) in delay-integration mode. It was shown that together with the traditional electron compensation of longitudinal motion of image, the compensation of transversal velocity of image motion is possible.

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1. INTRODUCTION

Charge-coupled devices (CCD) are widely used in modern systems of aerospace photographing. As is known, to obtain the maximum signal-to-noise ratio and, thus, the high level of resolution, it is necessary to synchronize the charge-carrier motion with the image motion, which is guaranteed in the so-called delay-integration mode [1]. This mode of a matrix CCD is characterized by the fact that the image motion velocity in the lens focal plain must be synchronized with the velocity of charge packets transfer along the columns of the CCD matrix. In practice, this synchronization is guaranteed by the two possible methods that can be applied independently:

(1) by the optical elements motion or by the so-called *optical-mechanical motion compensation*, or

(2) by the choice of charge packets transfer frequency in the CCD matrix, i.e., by *the electron compensation*.

Each of these methods has its own advantages and disadvantages, e.g.: the first one guarantees a wide dynamic range of compensable velocities but relatively low accuracy and performance because of large persistence of such moving elements as mirrors, prisms, and lens themselves; the second method has high accuracy and performance but has a limited dynamic range. Thus, real systems use both these methods simultaneously which makes it possible to minimize synchronization errors if we use them the most optimal way. In this paper, we consider a problem of optimal electron compensation as a problem of discrete-continuous system optimal control. In the following section we consider a general mathematical model image motion; then we consider a mathematical model of customary and generalized delay-integration modes and their characterization by its modulation transfer function. Then we devise an optimal control law of image motion synchronizing and in the conclusion we consider possible approaches to construction of optimal systems of image motion compensation.

2. AN IMAGE MOTION CALCULATION MODEL

We consider a system of image registration that is set on a mobile carrier and is used for photographing, e.g., an observed surface by remote sensing equipment set on an aviation or space carrier. At matrix CCD photographing when the camera moves with respect to a photographed object, to increase the signal-to-noise ratio, the CCD matrix usually works as a photosensitive elements measure and the camera scans the photographed fragment owing to its motion. With this photographing method, a sequential summation of signals registered by each elements of the column of matrix is conducted. The image "runs" across the matrix and creates a considerable data flow at the output that is stored in memories or is transferred in real time scale. When such systems projecting, as a rule, a problem of matching the photographing velocity with the camera motion occurs as an extensively high velocity of the relative motion requires decrease in exposure time and, thus, considerably decreases a dynamic range of equipment concerning lighting conditions. At the same time, a lot of modern cameras have a dynamic tracking capability of a photographed fragment by changing the direction of the sight line for decelerating the image motion velocity along the columns of the CCD matrix as it is shown in Fig. 1. With such photographing process, the image motion velocity forms a variable velocity field in the focal plain that depends on the current orientation of the optical axis defined by the angles $\theta(t), \phi(t)$ and the flight altitude $H(t)$. The general calculation method of the velocity field at arbitrary positional relationship of the camera and the photographing object is based on application of functional relationships that connect the coordinates of the point in the lens focal plain (ξ, η) and the point that is optical-conjugate to it (x, y) in the plain of the observed object at the current time t. We assume that the coordinate ξ corresponds to the transfer along the proper camera motion (e.g., flight direction at air photographing); and the coordinate η, to the transversal direction respectively. If the direct relations are given in the form

$$x = x(\xi, \eta, t), \quad y = x(\xi, \eta, t), \tag{1}$$

then for any t there exists an inverse transformation

$$\xi = \xi(x, y, t), \quad \eta = \eta(x, y, t), \tag{2}$$

and components of image motion velocity (V_ξ, V_η) in the lens focal plain are computed as follows [3–5]

$$\begin{pmatrix} V_\xi(\xi,\eta,t) \\ V_\eta(\xi,\eta,t) \end{pmatrix} = - \begin{pmatrix} \dfrac{\partial x}{\partial \xi} & \dfrac{\partial x}{\partial \eta} \\ \dfrac{\partial y}{\partial \xi} & \dfrac{\partial y}{\partial \eta} \end{pmatrix}^{-1} \begin{pmatrix} \dfrac{\partial x}{\partial t} \\ \dfrac{\partial y}{\partial t} \end{pmatrix} \Bigg|_{x=x(\xi,\eta,t), \quad y=x(\xi,\eta,t)}. \tag{3}$$

For concrete dependencies of the functions (x, y) on t and elements of the lens orientation, the relation (3) can be transformed to the form

$$\begin{pmatrix} V_\xi(\xi,\eta,t) \\ V_\eta(\xi,\eta,t) \end{pmatrix} = D_1(\xi,\eta,t) \begin{pmatrix} W_x \\ W_y \end{pmatrix} + D_2(\xi,\eta,t)\dot{\theta}(t) + D_3(\xi,\eta,t)\dot{\phi}(t), \tag{4}$$

where $D_i, i = 1, \ldots, 3$ are some functions that admit explicit analytic expressions, W_x, W_y are instantaneous velocities of the relative camera motion and the photographed surface point with $x = x(\xi, \eta, t)$, $y = x(\xi, \eta, t)$, and $\dot{\theta}(t), \dot{\phi}(t)$ are instantaneous angular velocities of optical axis rotation.

Thus, image motion velocities form a time-and-space variable field and variations of this field will be very small at the photographing time of one image element (accumulation of the light flux that comes from the photographed object domain which corresponds to the size of one photoreceiver

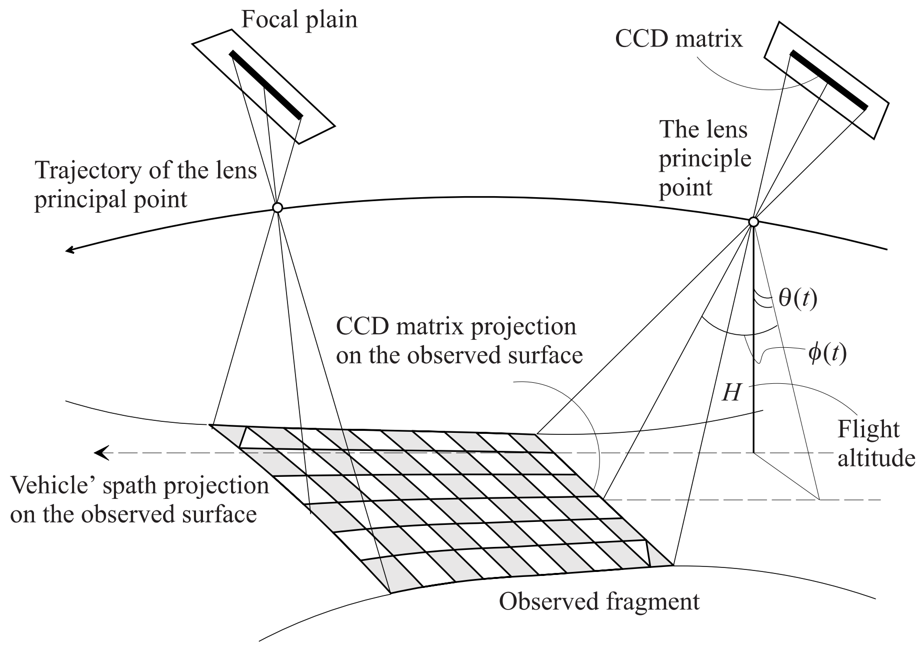

Fig. 1. Positional relationship of the camera and of the photographed element on photographing from the mobile carrier. The CCD matrix is situated in the lens focal plain, and the location of the sight line changes during photographing the fragment owing to the camera motion and the change of orientation. The camera motion is modeled by setting the trajectory of the lens principal point; we assume that the following is set: the flight altitude H, the lens focal distance, and the time function $(\theta(t), \phi(t))$, that define the orientation of the sight line (e.g., the direction of the lens optical axis) in the space.

element) but they change considerably during photographing the whole fragment. Consequently, we can single out two different space-time scales in the problem of image motion compensation to which the following different control mechanisms correspond:

—*microscopic* that exists within the light flux accumulation time (up to tens of milliseconds) from the domain size of decomposition element order in the transversal location and respectively from several decomposition elements (up to hundreds of microns) up to the whole column of the CCD matrix in the longitudinal location (units of millimeters),

—and *macroscopic* that corresponds to the photographing time of the whole fragment which lasts up to several seconds and stretches up to several thousands of CCD matrix elements in the transversal location, i.e., up to several tens of centimeters.

In the microscopic space-time scale, there functions the control of flux registration parameters (charge packets transfer frequency and the number of the transfers); in the macroscopic scale, the control of sight line orientation. The second mechanism is traditional for optical-mechanical systems; thus, in this paper, we place emphasis on the first mechanism.

3. DESCRIPTION AND CHARACTERISTICS OF THE DELAY-INTEGRATION MODE

CDD functioning in the customary delay-integration mode is sketched in Fig. 2. The light flux that comes from an element of the photographed object is accumulated by the lens and generates a charge packet during the accumulation phase which is proportional to the general light flux during the accumulation time; then during the transfer phase, this packet is transferred to the following row of the CDD matrix where it is summed with the charge packet, generated in this CDD matrix element in the following accumulation act. If the longitudinal image motion velocity is equal to the charge packets transfer velocity, then, as a result of the sequence of transfers and accumulations,

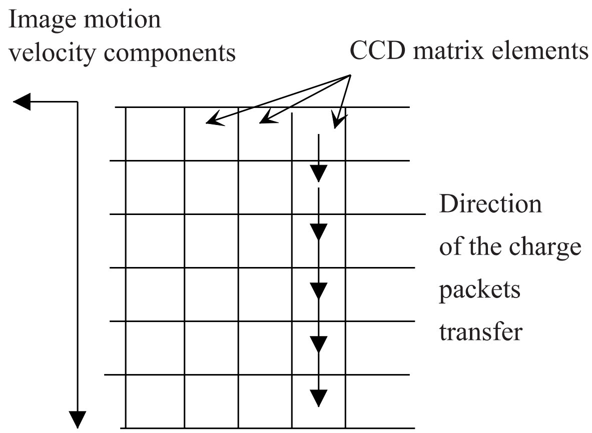

Fig. 2. Charge packets transfer along the columns of the CDD matrix in the customary delay-integration mode. On the left are shown image motion velocity components; on the right, the sequence of charge packet transfer along the columns of the CDD matrix.

the charge packet that corresponds to the registered element will increase so that the wanted signal will increase proportionally to the number of accumulation phases at passing the whole column of the CDD matrix. This mode is especially effective in photographing from the mobile carrier when, on the one hand, the photographed object is "scanned" owing to the carrier motion; on the other hand, at a very high motion velocity, optical-mechanical elements allow decreasing the image motion velocity by "stopping" the image or by decreasing the velocity of its motion in the focal plain up to the value such that the output data flow is sufficiently decreased and can be fixed in storage devices. Moreover, the wanted signal increase is necessary for achieving the maximum signal-to-noise ratio as in problems of air/space photographing the image contrast, as rule, is very low, and the importance of obtaining the picture is great. Readers that have some ideas about air photographing can find in this mode certain analogues with photographing by a slit aerocamera where the measure-elongated CDD matrix is an analogue of the slit; however, functional capabilities that occur on using optic-electronic registers of images are much larger.

The mathematical model of this process is space-time integration of the variable image field which is described by an equation

$$u(\xi, \eta, t) = U(\xi - V_\xi t, \eta - V_\eta t),$$

where in the microscopic scale we can consider the velocities V_ξ, V_η constant. Thus, the signal registered by a CDD matrix element (measure) with the number k at the time t_0 is equal to

$$C(t_0, k) = C_0 \sum_{n=1}^{N} \int\limits_{t_0+n\Delta T-\frac{\Delta T}{2}}^{t_0+n\Delta T+\frac{\Delta T}{2}} \int\limits_{nP_\xi-\frac{P_\xi}{2}}^{nP_\xi+\frac{P_\xi}{2}} \int\limits_{kP_\eta-\frac{P_\eta}{2}}^{kP_\eta+\frac{P_\eta}{2}} U(\xi - V_\xi t, \eta - V_\eta t) d\eta d\xi dt, \tag{5}$$

where

—N is a number of transfers in the longitudinal direction,

—ΔT is a period of a unit accumulation-transfer act,

—(P_ξ, P_η) are sizes of the CDD matrix element in the longitudinal and transversal directions respectively,

—(V_ξ, V_η) are image motion velocity components,

—C_0 is a normalizing constant that depends on the image brightness, CDD light-energy characteristics, and the optical system.

Modulation transfer function (MTF) that describes the transformation (5) in the spatial-frequency domain (ν_ξ, ν_η) is equal to

$$MTF(\nu_\xi, \nu_\eta) = \left| \frac{1}{N} \frac{\sin \frac{N(\nu_\xi(V_\xi \Delta T - P_\xi) + \nu_\eta V_\eta \Delta T)}{2}}{\sin \frac{\nu_\xi(V_\xi \Delta T - P_\xi) + \nu_\eta V_\eta \Delta T}{2}} \, sinc \frac{\nu_\xi P_\xi}{2} \, sinc \frac{\nu_\eta P_\eta}{2} \right|, \quad (6)$$

where $sinc(x) = \sin x / x$. From the Eq. (6) it follows that choosing

$$\Delta T_{opt} = \frac{P_\xi}{V_\xi}, \quad (7)$$

we can eliminate the MTF dependence on the velocity in the longitudinal direction; however, the dependence on the transversal component of the velocity V_η remains and results in a considerable MTF decrease at large values of N.

4. COMPENSATION OF IMAGE TRANSVERSAL MOTION ON APPLYING THE GENERALIZED DELAY-INTEGRATION MODE

The idea of the *generalized* delay-integration mode assumes the organization of a physical or virtual transfer of charge packets also in the transversal direction. With the physical transfer method, the CDD matrix can be divided by registers of transversal transfer as it is shown in Fig. 3 that function similarly to registers of transversal transfer used for signal pick up. With the virtual transfer, the matrix is divided into several matrices separated by registers of transversal transfer, but the signal from each column is summed with the transversal transfer.

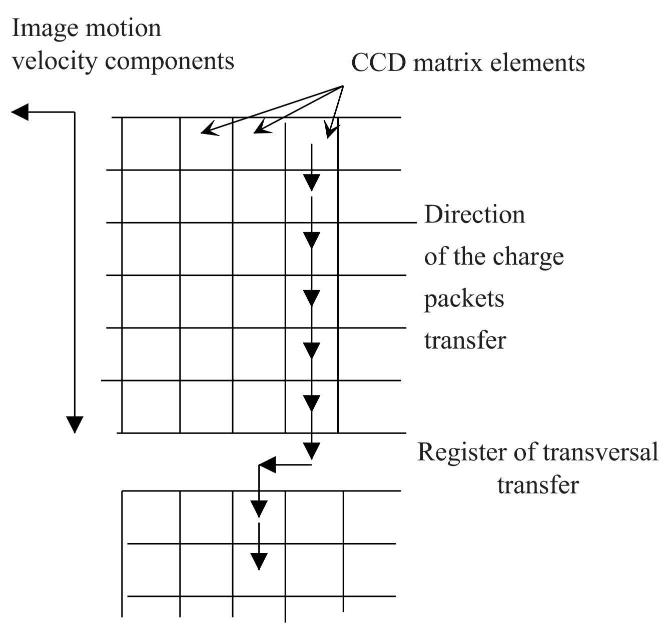

Fig. 3. Charge packets transfer along the columns of the CDD matrix with the *generalized* delay-integration mode. The basic motion in the longitudinal direction is shown as well as the physical and virtual transfers of charge packets in the transversal direction.

Both these mechanisms are equivalent regarding the influence on the quality of the picked up signal and are described by the following analogue of the Eq. (5)

$$C(t_0,k) = C_0 \sum_{m=1}^{M} \sum_{n=N_1(m-1)+1}^{N_1 m} \int\limits_{t_0+n\Delta T-\frac{\Delta T}{2}}^{t_0+n\Delta T+\frac{\Delta T}{2}} \int\limits_{nP_\xi-\frac{P_\xi}{2}}^{nP_\xi+\frac{P_\xi}{2}} \int\limits_{(k+\eta_m)P_\eta-\frac{P_\eta}{2}}^{(k+\eta_m)P_\eta+\frac{P_\eta}{2}} U(\xi - V_\xi t, \eta - V_\eta t) d\eta d\xi dt, \quad (8)$$

where

—M is a number of possible transfers in the transversal direction,

—η_m is a quantity of the transversal transfer in the mth period, $m = 1, \ldots, M$, i.e., $\Delta\eta_m \in \{-1, 0, 1\}$,

—$MN_1 = N$.

The expression for the modulation transfer function has the form

$$MTF(\nu_\xi, \nu_\eta) = \left| \frac{1}{M} \sum_{m=1}^{M} e^{i\nu_\eta[P_\eta \eta_m - V_\eta \Delta T(N_1(m-1)+1)]} \right|$$

$$\times \left| \frac{1}{N_1} \frac{\sin \frac{N_1(\nu_\xi(V_\xi \Delta T - P_\xi) + \nu_\eta V_\eta \Delta T)}{2}}{\sin \frac{\nu_\xi(V_\xi \Delta T - P_\xi) + \nu_\eta V_\eta \Delta T}{2}} \, sinc \frac{\nu_\xi P_\xi}{2} \, sinc \frac{\nu_\eta P_\eta}{2} \right|. \quad (9)$$

5. OPTIMAL CONTROL AT THE TRANSVERSAL TRANSFER COMPENSATION

We point out that as in case of the customary delay-integration mode, the choice of the relation (7) guarantees a complete image motion compensation in the longitudinal direction, and for a compensation of transversal transfer we should maximize the first cofactor in the Eq. (9) by choosing the piecewise constant function η_m. We point out that with small values of indices, the module of the sum of exponents sum admits decomposition of the form "unity minus half of the sum of squared indices,"; thus, the maximization problem of the corresponding MTF cofactor is reduced to the minimization problem of the sum of squared indices or to the problem of finding the best in the mean-square sense approximation of the linear function. This allows choosing the optimal (suboptimal) control η_m, that depends on the velocity V_η. The optimal function η_m, that minimizes the mean-square deviation from the linear function $V_\eta \Delta T(N_1(m-1)+1)$ is equal to (we assume that $V_\eta > 0$)

$$\eta_1 = 0,$$

$$\eta_m = \begin{cases} \eta_{m-1}, & \text{if} \quad |P_\eta \eta_{m-1} - V_\eta \Delta T(N_1(m-1)+1)| \le \dfrac{P_\eta}{2} \\ \eta_m = \eta_{m-1} + 1, & \text{otherwise.} \end{cases} \quad (10)$$

Results of the numerical analysis are shown in Fig. 4 where is given the dependence of MTF on normalized values of the variables

$$\nu_\eta P_\eta \pi \in [0,2] \quad \frac{\nu_\xi P_\xi}{\pi} = 1,$$
$$\frac{V_\xi}{V_\eta} = N_1 = 8, \quad \frac{P_\xi}{P_\eta} = 1,$$
$$\Delta T = \frac{P_\xi}{V_\xi}(1+k), \quad k = 0,\ 0.001,\ 0.003,\ 0.005,\ 0.01.$$

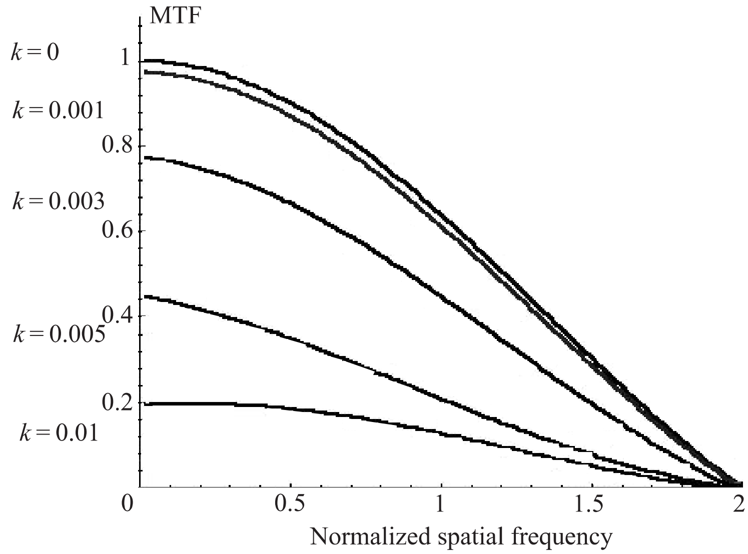

Fig. 4. The value of the modulation transfer function (MTF) that corresponds to the optimal compensation of longitudinal and transversal components. The terms with *sinc* functions that are specified by space integration of the light flux over the area of the CDD matrix element are rejected so that we single out only the compensation component.

The chosen values of the parameters are critical to some extent since the normalized value of spatial frequency, equal to 1, corresponds to the Nyquist frequency; the relation of velocities, equal to N_1, corresponds to the maximum value of transversal velocity which can be compensated; different curves correspond to possible synchronization errors expressed in terms of the parameter $k = \dfrac{\Delta T - \Delta T_{opt}}{\Delta T_{opt}}$.

6. CONCLUSIONS

As it follows from the results of the numerical analysis, the correct selection of control parameters $\Delta T, \eta_m$, $m = 1 \dots M$ makes it possible to compensate the image motion within certain limits by electron compensation methods. At the same time, it is necessary to point out that on changing the synchronization accuracy from 0.1% to 1%, the MTF value decrease is very considerable and together with it the system resolution decrease as a whole. Moreover, even within the limits of one photographed fragment, the parameters that guarantee a high level of resolution can change considerably. This determines the necessity for the construction of control system of image motion compensation which can be related to the class of problems of optimal stochastic control of discrete-continuous systems with incomplete data. The general approach to solving such problems includes two stages:

—estimation of current velocity of image motion taking into consideration carrier dynamics and the position of the sight line;

—calculation of optimal parameters of control and their application in fragment photographing.

First stage problems are solved on basis of standard estimation methods of motion parameters of dynamic systems and the following direct calculation of image motion velocities. However, the accuracy of such estimates can be insufficient for achieving the high level of the signal-to-noise ratio; then the necessity for the definition of velocities directly by the registered image occurs. Systems of this type belong to the class of correlation-extremal follow-up systems [2] and are based on the dynamic coincidence of the sequence of registered images. Application of nonlinear estimation

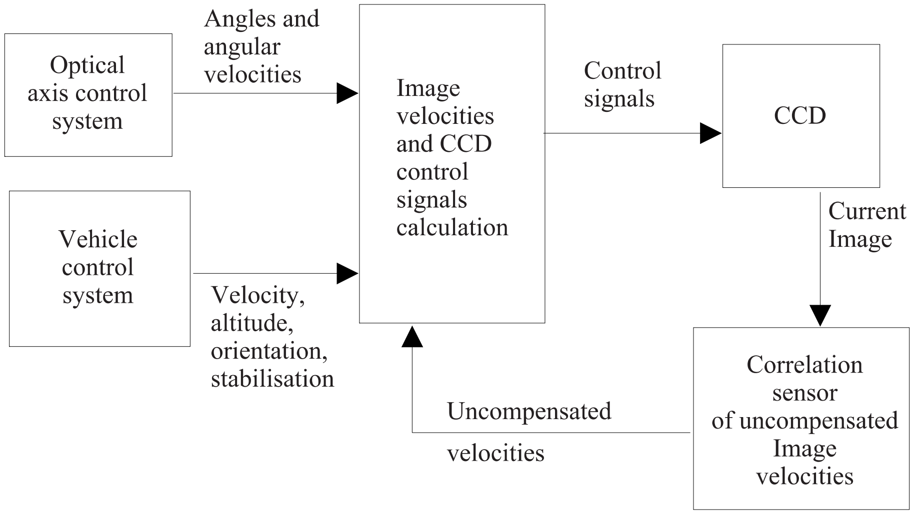

Fig. 5. Control system of image motion compensation.

methods allows achieving a very high level of accuracy of coincidence which gives hope that the definition accuracy of uncompensated remaining velocities is high. The general structural scheme of control system is shown in Fig. 5.

The research on precision characteristics of such control systems is a very urgent problem, whose solution is necessary for the construction of high resolution systems. Specialists in projection of photographing systems from mobile objects know very well the stabilization problem when excellent optical systems with a large focal distance and, respectively, a high level of resolution cannot achieve their potential capabilities because of the resolution decrease due to the blurred picture. Electron compensation methods proposed in this paper suggest some of possible approaches to solving this problem.

REFERENCES

1. Barbe, D.F., Delay/integration Mode in Image Detectors, in *Solid State Imaging*, Jespers, P. et al., Eds., Leiden: Noordhoff, 1976.

2. Baklitskii, V.K. and Yur'ev, A.N., *Correlation-Extremal Navigation Systems*, Moscow: Radio i Svayz', 1982.

3. Miller, B.M., Fedchenko, G.I., and Morskova, M.N., Image Motion Calculation on Panoramoc Photographing, *Izv. Vyssh. Uchebn. Zaved., Geod. Air Photogr.*, no. 4, pp. 81–89, 1984.

4. Miller, B.M. and Fedchenko, G.I., Influence of Carrier Orientation Errors on Image Motion at Photographing from a Moving Object, *Izv. Vyssh. Uchebn. Zaved., Geod. Aerofotos"emka*, no. 5, pp. 75–80, 1984.

5. Kistlerov, V.L., Kitsul, P.I., and Miller, B.M., Computer-aided Design of the Optical Devices Control Systems Based on the Language of Algebraic Computation FLAC, *Math. Comput. Simulation*, 1991, vol. 33, no. 4, pp. 303–307.