The method and structural scheme of an information-measuring system for determining the parameters of objects' movements (technological equipment in the quarry for extracting block natural stone) have been proposed. A distinctive feature of time video sequences containing images of measured objects is their adaptation and adjustment in accordance with the intensity of movement and accuracy requirements for measurement results. Structural and software-algorithmic methods were also applied for improving the accuracy of measurements of motion parameters, namely: complexation of two measuring channels and exponential smoothing of digital references. One of the measuring channels is based on a digital video camera, the second is based on an accelerometer mounted on an object and two integrators. Exponential smoothing makes it possible to take into consideration the previous countdowns of movement parameters with weight coefficients. That ensures accounting for the existing patterns of movement of the object and reducing the errors when measuring the parameters of movement by (1.4...1.6) times.

The resulting solutions have been implemented in the form of an information and measurement system. The technological process of extracting blocks of natural stone in the quarry was experimentally investigated using a diamond-rope installation. Based on the contactless measurement of motion parameters, it is possible to ensure control over this process and improve the quality of blocks made of natural stone.

Based on the experimental study of measurement errors, recommendations were given for the selection of adaptive parameters of a video sequence, namely the size of images and the value of the inter-frame interval. In addition, methods for the software-algorithmic processing of measuring information were selected, specifically exponential smoothing and averaging the coordinates of the contour of an object, measured in 30 adjacent lines of the image

Keywords: motion parameters, software-algorithmic processing of measuring video information, exponential smoothing, complexation

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DEVISING A METHOD FOR MEASURING THE MOTION PARAMETERS OF INDUSTRIAL EQUIPMENT IN THE QUARRY USING ADAPTIVE PARAMETERS OF A VIDEO SEQUENCE

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1. Introduction

Measurements of various mechanical quantities are widely used at enterprises for the extraction and processing of natural stone. This includes the moving and motion parameters of industrial objects. The results of these measurements are used to manage production processes and comply with technological norms in the manufacture of articles made of natural stone, as well as to control their quality and increase competitiveness [1–4].

To acquire data on the objects' movements, various contact and contactless technologies and devices can be used: accelerometers, gyroscopic transducers, radio frequency identification, navigation systems with GPS devices, the construction and processing of time video sequences.

The development of modern information-measuring systems requires both the improvement of structural solutions and the development of software-algorithmic methods for processing measuring information. In addition, an important task is to devise contactless measurement methods, for example, based on video information about a given object [1, 5–9].

The time sequences of measured objects' images contain measuring information about the mechanical quantities that characterize these objects. Underlying the contactless measurements of motion parameters in this study is the transformation of visual information about measured objects into digital images and the execution of software-algorithmic processing of the derived time sequences of these images. By software-algorithmic processing, mechanical quantities such as current coordinates and motion parameters of measured objects are determined. The specified parameters may be self-sufficient or form the basis for determining other properties of measured objects. Given this, it is possible to control the spatial position and movement parameters of objects [3]. In addition, contactless methods and measuring tools can control the technological processes and quality of industrial articles during their manufacture [1].

This approach will provide the measurement of the parameters of objects' movements in real time with increased accuracy and performance, advanced functionality compared to existing measuring tools.

One of the applied tasks for the use of means of measuring motion parameters based on time video sequences can be real-time control over technological processes of extraction and processing of block natural stone [10].

Movements of technological equipment in the quarry are controlled indirectly, without the possibility of obtaining instantaneous values of movements and speeds of motion. For example, the magnitude of movements and the operation of technological equipment are controlled by the value of the main electric drive current. If speeds are measured, then this is carried out by contact methods using measuring transducers (for example, electromechanical tachometers) [10].

To improve the quality of articles, it is necessary to receive and analyze in real time the instantaneous values of movement parameters for all modes of operation of technological equipment. However, current approaches, methods, and measuring instruments give integrated values of measured values with large dynamic errors under the variable modes of equipment operation.

Therefore, unresolved priority tasks when measuring the parameters of objects' movements (technological equipment in the quarry) are the development and study of contactless methods for measuring motion parameters. At the same time, it is important to obtain and analyze the instantaneous values of measured values in real time for modes of operation of technological equipment with variable parameters. In addition, an important task is an adaptation of measuring instruments to difficult conditions characteristic of stone mining and stone-working enterprises.

As a result of solving those tasks, it is possible to ensure the improvement of the quality and competitiveness of industrial articles made of natural stone. Therefore, it is a relevant task to study the development of a method for measuring the parameters of the objects' movements with adaptive parameters of a video sequence.

2. Literature review and problem statement

Most available hardware, as well as methods and algorithms for constructing and software-algorithmically processing digital images are focused on achieving a certain level of visual image quality when perceived by humans. Existing solutions to scientific and technical problems, in which mechanical quantities are determined on the basis of algorithmic processing of two-dimensional digital images of objects, are highly specialized in nature or use outdated algorithms and hardware. Those technological advances for two-dimensional signals do not employ modern methods of information and computer technologies (for example, artificial neural networks and optimization methods) and are designed mainly to improve the visual quality of images.

Paper [1] reports the results of studying the use of digital images to optimize the technological processes of extraction of natural stone blocks. The fundamental possibility of determining the parameters of technological processes and articles by these images is shown. However, the issues related to metrological aspects of measurements and determining the parameters of objects' movement remained unresolved. The reason for this may be the lack of measurement specialists when conducting that study.

Paper [7] examines the dynamic errors of measurements of geometrical parameters and parameters of objects' movements. However, there are no proposals to reduce such failures in practical tasks characterized by complex measurement conditions. Therefore, the results of the cited paper need to be improved to determine the time-dependent parameters of the movement of technological equipment elements in the quarry.

Study [8] also misses accuracy estimates and measures to improve the accuracy of measurements of motion parameters. Therefore, the reported results should be summarized and improved in order to determine the parameters of objects' movements.

Work [9] reports the development of a computerized system to assess the trajectory of objects in the airspace. However, the metrological aspects of such measurements were not investigated.

Paper [11] examines mathematical models and algorithms of image processing, which may in the future be an integral part of time video sequences with measuring information. These results can be the theoretical basis for estimating errors in determining the geometrical parameters and parameters of motion of objects.

Study [12] focuses on statistical assessments of the quality of objects by their images. However, there are no estimates regarding the accuracy of measurements of geometrical parameters of objects by their images and motion parameters. Therefore, the results reported should be summarized and improved in order to determine the parameters of objects' movements.

Paper [13] proves a fundamental possibility of exploring the parameters of different processes and objects by their images. However, the issues related to the metrological aspects of measurements remained unresolved.

Study [14] focuses on the development of accelerator and motion meters for mobile robots based on MEMS sensors and ultrasonic rangefinders using signal filtration methods. Paper [15] reports the development of a computerized sensory system for measuring distances and angles to objects. However, in the cited studies there is no use of contactless measurements, measuring video information and methods of combining several measuring channels to increase the accuracy of measurement of specified mechanical quantities.

In [16], the use of matrix "light signal" converters and methods based on artificial neural networks for precision measurements of angular values were substantiated; but the issues of determining the parameters of movement of the objects under investigation were not considered.

In the reviewed works [1, 7–9, 11–14], the problem of obtaining and analyzing instant values of measured values in real time for modes of operation of technological equipment with variable parameters has not been solved. Software-algorithmic and structural measures to improve the accuracy of results in contactless methods of measuring motion parameters are not fully investigated. In addition, the complex conditions of measurements characteristic of stone mining and stone-working enterprises that lead to touch error measurements are not taken into consideration; measures for adaptation of measuring instruments to these conditions are not determined.

Our review [1, 7–9, 11, 14] confirms that it is advisable to study the ways of using information and computer technologies for processing digital images and their sequences to measure the parameters of objects' movements in real time. To do this, it is necessary to devise a method for measuring the parameters of objects' movements based on computerized processing of time sequences of measuring video information in real time. The results of measurements and calculations of motion parameters must be stored, organized, transformed, calculated, compared, evaluated, represented graphically, updated. Therefore, the task is to build an information-measuring system to determine and control the parameters of objects' movements involving software-algorithmic image processing.

3. The aim and objectives of the study

The purpose of this work is to increase the accuracy and speed, to expand the functionality of the means of measuring the parameters of the movement of technological equipment in the quarry for the extraction of block stone by devising a measurement method with adaptive video succession parameters. The implementation of this method in the form of an information-measuring system could make it possible to improve the procedures for controlling technological processes at stone mining and stone-working enterprises.

To accomplish the aim, the following tasks have been set:

– to devise a method for measuring the parameters of objects' movements with adaptive parameters of video sequences, which are adjusted in accordance with the current conditions of measurements, as well as the structure of the information-measuring system corresponding to this method;

– to determine the sequence of formation and processing of time video sequences with measuring information about the parameters of objects' movements;

– to experimentally investigate the method and information-measuring system using an example of determining and controlling the parameters of movement of the diamond-rope installation for extracting blocks of natural stone in the quarry;

– based on data from an experimental study, to determine the best adaptive parameters of video sequences in terms of their accuracy and speed, and to evaluate the accuracy of the results obtained while determining the parameters of objects' movements.

4. The study materials and methods

Devising a method for measuring the parameters of objects' movements (the first task of our research) is based on the use of time sequences of images (video sequences) of measured objects. Motion parameters are movement, speed, acceleration. Movements are found in two or three coordinates on a plane or in space. That is, the initial data, determined on the basis of a video sequence, are the current coordinates of objects; all other movement parameters are calculated and processed by software-algorithmic methods.

At the same time, geometric parameters and current coordinates of these objects are recorded on each image, and changes in the time of the specified parameters and coordinates characterize the movement of measured objects.

To obtain time video sequences, technical means of formation of video sequences and software-algorithmic means of their processing are used. Technical means include a digital video camera; a tripod that makes it possible to fix the camera; test objects with known linear dimensions; a computer or microprocessor device for processing video sequence and calculating motion parameters. Software and algorithmic means provide the acquisition of measuring information about current coordinates and motion parameters from a video sequence, as well as increase the accuracy of determining motion parameters. Together, all these means form an information and measurement system to determine the parameters of objects' movements.

Several displacement parameters can be measured based on images, geometrical parameters, and the current coordinates of objects. The basis of measurements of motion parameters is the current coordinates of the contour points of the measured object [5, 6, 8].

These geometric parameters are measured directly by the current video sequence frame and are used for numerical calculations of the motion parameters of the measured object.

Any complex movement of the measured object is represented as the sum of the translational movement of its center of masses and the rotation of the object around this center of masses.

Measurement of motion parameters and their mathematical notation are executed depending on the application problem in three-dimensional space or on the plane. This involves a vector sum of projections of motion parameters on coordinate axes to determine general motion parameters and one or more video sequences obtained from different points of three-dimensional space.

In calculating the parameters of movement, numerical methods of differentiating the current values of the coordinates of the object are used in the simplest case. To increase the accuracy, one can use a polynomial approximation of the arbitrary trajectory of the object of measurement [17, 18].

To increase the accuracy of the method of determining motion parameters, it is advisable to use structural and software-algorithmic methods to improve the accuracy of measuring instruments. This is, for example, the use of two measuring channels in the construction of the information-measuring system, averaging the coordinates of the path in adjacent lines of the image, exponential smoothing of the calculated values of motion parameters, adaptive adjustment of time video sequence parameters.

Since the method of determining motion parameters employs the software-algorithmic processing of images, it is necessary to determine the sequence of formation and processing of time video sequences with measuring information about the parameters of objects' movements. This is the second task of our research.

To do this, in the process of determining the parameters of motion, a video sequence is formed, which contains significant differences in brightness and/or color between the subject and the background. It is then divided into individual frames according to the current adaptive settings; in the frames, one measures the geometry and current coordinates of objects. This is done by averaging the results of measurements of the current coordinates of the object's path in several adjacent rows, in which an image of the object is available based on the results of segmentation of the frame to the measurement object and background.

The current coordinates and other geometric parameters are determined by relating to discrete points (d.p.) that make up the digital image. Therefore, a large-scale coefficient is additionally used to obtain current coordinates not in discrete points of the image but in generally accepted units of length. This large-scale coefficient is pre-calculated based on the study of images of test objects with known linear dimensions. Next, the movement, speed, acceleration of objects based on the current coordinates of objects, numerical differentiation methods, and software-algorithmic methods for improving the accuracy of determining motion parameters are calculated.

To confirm the possibility of practical use of the devised measurement method, it is necessary to tackle the third task of our research. It implies an experimental study of the method and information-measuring system using an example of determining and controlling the movement parameters of the diamond-rope unit for extraction of blocks of natural stone in the quarry.

The main object of measurements was technological equipment in a quarry for the extraction of block natural stone. The movement of the diamond-rope installation in the process of separating blocks of natural stone from the rock massif of the deposit was investigated.

We determined motion parameters according to the devised method of measurement using time video sequences containing images of technological equipment. For the experimental study, an information and measurement system was built on the basis of technical and software-algorithmic means of formation and processing of time video sequences.

The movement of the diamond-rope installation along the horizontal axis of coordinates was determined. This movement is due to the displacement of the installation during the technological process in the quarry.

Since the parameters of a video sequence, which are formed in the process of measurements, must be adjusted in accordance with the current values of the parameters of movement and conditions of measurements, it is necessary to solve the fourth task of our study. It implies determining, according to the experimental study, the best parameters of video sequences in terms of accuracy and performance.

In addition, the accuracy of the results obtained while determining the parameters of movement was assessed. For this purpose, a time video sequence was additionally formed, which provides significantly higher accuracy of motion parameters compared to the sequences under study. Statistical methods of experimental data processing, determining the average and rms values and confidence error interval were used to process experimental results and determine motion parameters errors.

5. Results of studying the method and information-measuring system for determining the parameters of objects' movements based on time video sequences

5. 1. Devising a method for measuring the parameters of movement and the structure of an information-measuring system

Determining the parameters of objects' movements (technological equipment in the quarry) is proposed to be carried out on the basis of the formation and software-algorithmic processing of video sequences containing a number of images of these objects at fixed moments. The main operation is to obtain from such images the current coordinate values of the measured objects and calculate, on this basis, the movements, speeds, and accelerations of these objects. A significant difference of the devised method is the use of software-algorithmic and structural operations to increase the accuracy of the results of measuring motion parameters.

Any complex movement of a measured object is represented as the sum of the translational movement of its center of masses and the rotation of the object around this center of masses. The time-based video sequence frame makes it possible to obtain the current coordinates of the measured object on the xOy plane, which coincides with the plane of the light-sensitive matrix of the "light signal" converter, accordingly, the measurement of motion parameters is carried out on the plane.

Movement (movement $dr_i = r_i^* - r_{i-1}^*$, speed $v_i = \frac{dr_i}{dt}$, and acceleration $a_i = \frac{dv_i}{dt}$) are determined by each of the x and y coordinate with a summary of the obtained results to the vectors of movement, speed. and acceleration (r_i^* is the current value of the x or y coordinate measured by the i-th image or at the time t_i). The simplest method for determining the parameters of movement, in this case, is numerical differentiation [18–20].

Numerical differentiation [18, 20] for each coordinate in the measurement process (real time) is performed by the formulas:

$$v_i = \frac{dr_i}{dt} = \frac{r_i^* - r_{(i-q)}^*}{q\cdot\delta}, \quad q = 1,2,3,\ldots,$$

$$a_i = \frac{d^2 r_i}{dt^2} = \left[\frac{dr_i}{dt} - \frac{dr_{(i-q)}}{dt}\right] / \, dt = \frac{r_i^* - 2r_{(i-q)}^* + r_{(i-2q)}^*}{(q\cdot\delta)^2}, \tag{1}$$

and for data accumulated in the storage device:

$$v_i = \frac{r_{(i+q)}^* - r_{(i-q)}^*}{2\cdot q\cdot\delta}, \quad a_i = \frac{r_{(i+q)}^* - 2r_i^* + r_{(i-q)}^*}{(q\cdot\delta)^2}, \tag{2}$$

where δ is the inter-frame interval (sampling step) of the time video sequence;

q is the number of frames by which the corresponding coordinate count is shifted relative to the current time.

If one wants to evaluate the instantaneous values of motion parameters, then q=1. If parameters are evaluated at a certain interval of observation, then q>1 [7, 17].

Here's the task to determine, by the numerical calculation, motion parameters based on the measured values of geometrical parameters and current coordinates of the object. The simplest and known methods are numerical differentiation for calculating the speed and acceleration of the object. However, numerical differentiation methods do not take into consideration the presence of error in the measured coordinate counts.

Measurements of current coordinates are carried out with error Δ_r. The accuracy of these measurements is enough to determine the MO geometrical parameters.

Errors in measuring the current coordinates of an object in an image contain the following components [6–8]:

1. Discreteness error, determined by the number of discrete dots per mm in a digital image.

2. Video signal quantitation error level. This error is calculated by the number of binary digits used to encode digital color/brightness information at each discrete point in the image.

3. Distorted shape of the video signal. This error occurs due to the limitation of the video signal frequency band,

which negatively affects the reproduction of object outlines in the image. This leads to a systematic component of the error in determining the coordinates of MOs.

4. Geometric distortions. This error occurs in the optical system of imaging devices.

5. Noises available in electrical circuits of video sequence devices.

As a result of numerical differentiation, these coordinate errors are converted (transformed) into even greater errors in determining the speed and acceleration of objects. Let us consider in detail the transformed error, using the rules for converting errors of input values during calculations [20]. This error is the most significant in identifying the parameters of the movement of MOs by the method of numerical differentiation.

The transformed errors in determining the speed and acceleration of measured objects for each coordinate for (1) and (2) are [7, 18]:

$$\Delta_{v\text{тр}} = \frac{2\Delta_r}{q\cdot\delta}, \quad \Delta_{a\text{тр}} = \frac{4\Delta_r}{(q\cdot\delta)^2}, \tag{3}$$

$$\Delta_{v\text{тр}} = \frac{\Delta_r}{q\cdot\delta}, \quad \Delta_{a\text{тр}} = \frac{4\Delta_r}{(q\cdot\delta)^2}. \tag{4}$$

The largest transformed error will be in the following cases according to (3), (4): when determining the instantaneous values of movement parameters q=1; in the study of fast-moving MOs, based on video sequence with a high frame rate (δ<<1).

Therefore, it is necessary to devise methods that are insensitive to the errors of the current coordinates and provide high accuracy in determining the parameters of objects' movements.

The following solutions are possible:

1. Application of the method of exponential smoothing of coordinates and motion parameters.

2. Complexation of several measuring channels, which are based on different physical principles of obtaining measuring information about the parameters of the movement of the object.

3. Using the adaptive step of taking the countdown of measuring information (the inter-frame interval in a video sequence, the interval between the input of the countdown from the accelerometer).

The exponential smoothing method involves sequential smoothing of MO trajectory parameters using a filter with constant weight coefficients and a fixed number of input current countdowns. The principle of operation of this method is as follows: preliminary counts of movement parameters are taken into consideration with weight coefficients falling according to the exponential law for calculating the current smoothed parameter [17].

For any scalar parameter of movement θ (it can be r – coordinate, v – speed, or a – acceleration), the exponential smoothing formula takes the form [19]:

$$\hat{\theta}_i = (1-\xi)\theta_i + \xi f[\hat{\theta}_{i-1}, \hat{\theta}_{i-2}, \ldots, \hat{\theta}_{i-q}], \tag{5}$$

where θ_i is the measured value of the motion parameter in the i-th step; $\hat{e}_i$ – the smoothed value of the movement parameter in the i-th step; f[...] – some function from the previous smoothed values of the motion parameter; ξ is a constant value in the sense of the smoothing coefficient. It can be $0\le\xi\le1$.

To further increase the accuracy of measurements of motion parameters, it is necessary to combine the results of measurements obtained in several measuring channels based on different physical principles and have independent statistical characteristics of the error.

To measure the parameters of movement, a complexation is proposed according to the filtration scheme [21]. With the simultaneous operation of several measuring devices that use different physical principles, their output signals after passing through the filters are added, which increases the accuracy of the measuring parameter.

In the instrumentation system, the filtration scheme has symmetry in the processing of incoming information, all the meters in it seem to be "equal". The results of measurements of K signals containing the measured value r and errors (interference) $\phi_1, \phi_2, \ldots, \phi_K$:

$$r_{i1}^* = r_i + \phi_{i1}; \quad r_{i2}^* = r_i + \phi_{i2}; \quad \ldots; \quad r_{iK}^* = r_i + \phi_{iK}, \tag{6}$$

after passing K filters are added (Fig. 1). The output signal is [21]:

$$r^*(p) = \left[\sum_{k=1}^{K}\Phi_k(p)\right] r^*(p) + \sum_{k=1}^{K}\Phi_k(p)\phi_k(p), \tag{7}$$

where p is the Laplace operator.

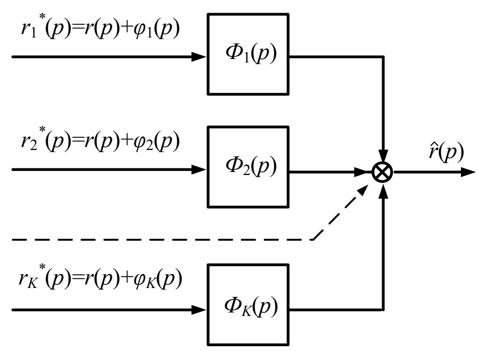


Fig. 1. Complexation of measuring channels according to the filtration scheme

To measure variable values of motion parameters, numerical methods with adaptive pitch are effective.

They are based on solving plausibility equations for the case of estimation of parameters of linear trajectory. This case is essential for practice because any trajectory at a limited observation interval can be represented as a linear polynomial (first-power polynomial) [17].

As the initial values of the movement parameters, we adopt the coordinate r_0 and the speed v_0 at the initial moment t_0. The law of coordinate change is represented as:

$$r(v,t) = r_0 + v\times(t-t_0), \tag{8}$$

and the coordinate estimation at the time t_i is:

$$\hat{r}_i = \hat{r}_{i-1} + \hat{v}_{i-1}\tau_i, \tag{9}$$

where $\tau_i=t_i-t_{i-1}$ is the current value of the adaptive inter-frame interval of a video sequence.

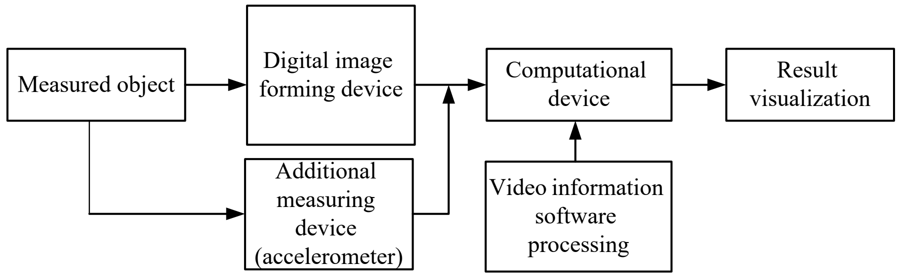


Fig. 2. Information-measurement system for determining the parameters of objects' movements based on time video sequences

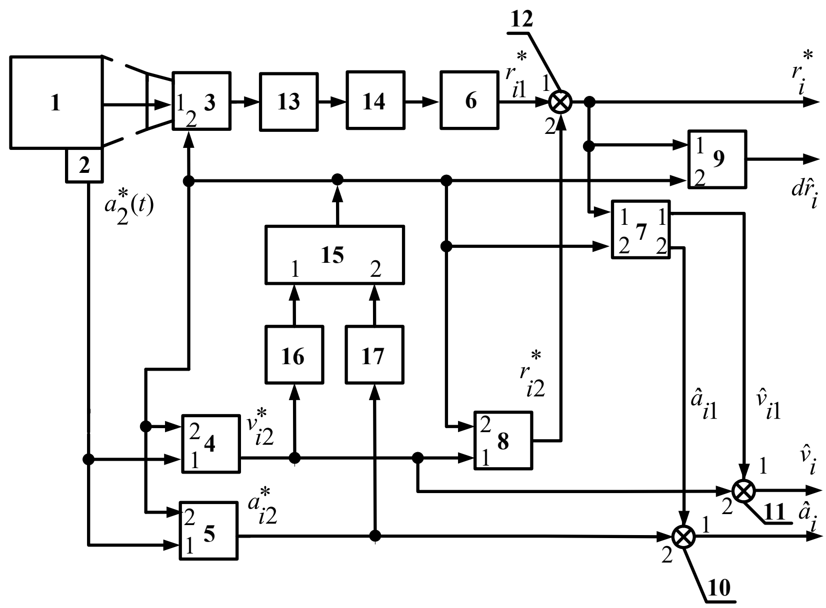


Fig. 3. Structural diagram of the information-measuring system

The equation for calculating the estimation of linear trajectory parameters when using more than one previous value is [17]:

$$\hat{r}_i = \sum_{j=0}^{q} \eta_r(j) r_{i-j}^*, \tag{10}$$

$$\hat{v}_i = \sum_{j=0}^{q} \eta_v(j) r_{i-j}^*, \tag{11}$$

where $\eta_r(j)$ and $\eta_v(j)$ are the weight coefficients to take into consideration the coordinate and velocity values measured in previous moments, respectively.

The sampling step (inter-frame interval) $\tau_i = t_i - t_{i-1}$ in (5) to (9) may change during measurements depending on the results of a rough estimation of current values of motion parameters.

With the help of preliminary estimates of motion parameters in the process of measurements, an inter-frame interval of a video sequence and an interval between adjacent acceleration, speed, and coordinates of the measured object processed by software-algorithmic methods are formed.

At moments of change in movement parameters, the inter-frame interval, and the interval between adjacent countdowns of the measuring information processed are reduced.

Due to this decrease, the countdown of measuring information is closer to the current time and describes changes in the parameters of motion occurring with lower dynamic errors.

Based on the devised method for determining the parameters of movement with adaptive parameters of a video sequence, a structural scheme of the information-measuring system was built.

In the structural scheme, we shall use a combination of two measuring channels according to the filtration scheme and build an information and measurement system to determine the parameters of objects' movements based on time video sequences (Fig. 2).

It consists of a digital image forming device (video camera, main measuring channel) and an additional measuring device (for example, an accelerometer, an additional measuring channel), a computational device, and software-algorithmic support that calculates the results of measurements of motion parameters.

The hardware implementation of the information-measuring system [22] contains the following units (Fig. 3): 1 – object of measurement; 2 – accelerometer; 3 – imaging device; 4 – first integrator; 5 – lower frequencies filter; 6 – unit for determining current coordinates; 7 – speed and acceleration detection unit; 8 – the second integrator; 9 – displacement calculation unit; 10 – the third adder; 11 – the second adder; 12 – the first adder; 13 – analog-digital converter; 14 – memory unit: 15 – unit for setting time intervals: 16 – the first element of delay: 17 – the second element of delay.

The designed information-measuring system implements an approach using two measuring channels. Obtaining countdowns of the current coordinate and accelerations is carried out with an adaptive step, which depends on the speed of movement of the object. A rough estimate of this speed is formed in units 15–17 and is used to adjust the interval for obtaining current countdowns in units 3–5. The countdowns of current displacements, speed, and acceleration calculated in units 7, 9 can be further smoothed by the exponential method.

Thus, all three proposed approaches to improving the accuracy of determining the parameters of objects' movements are involved in the designed information-measurement system.

5. 2. The sequence of formation and processing of measuring information about the parameters of objects' movements

The devised method for determining motion parameters is based on the formation and software-algorithmic processing of measuring information. The source of this information is the time video sequence and, if necessary, signals from the accelerometer mounted on technological equipment.

Therefore, it is necessary to determine the sequence of formation and processing of measuring information according to the proposed method for measuring the parameters of movement of technological equipment in the quarry. When performing specific operations, software and algorithmic tools and the structure of the information-measuring system were taken into consideration, aimed at improving the accuracy of determining the parameters of movement in real time. The basis for determining the parameters of objects' movements is the gradual processing of time video sequences by software-algorithmic support to the information-measuring system.

To obtain data on geometrical parameters and motion parameters, one must:

1. Form a video sequence. To do this, first apply a mark to the measured object that locks the current position of the object, or use the existing significant differences in brightness and color between the subject and the background. Video sequence settings must be adjusted according to the current measurement conditions and a priori information about possible values of motion parameters.

2. Divide the video sequence into individual frames according to the camera specifications (the number of frames per second) and measure the geometry and current coordinates of the objects.

3. Determine the current coordinates of objects to calculate their movement parameters. This can be done in different ways, depending on the requirements for the accuracy and speed of the information-measuring system:

– measure the current coordinates of the object's path in one fixed line for each frame;

– average the results of measurements of the current coordinates of the object's path in *n* adjacent lines ($1 \le n \le N$, where N is equal to the number of rows in which the image of the object is based on the results of segmentation of the frame to the measured objects and background);

– measure the coordinates of the center of masses of the object.

4. Programmable image processing, which gives the current coordinate values in the discrete points of the image (that is, it is the row number and column with a contour point). The digital image in the computer is stored and processed as a matrix, the elements of which characterize the brightness or color of the corresponding points on the surface of the measured object [5]. That explains the use, in intermediate calculations, of coordinates expressed in discrete points (d.p.). In accordance with the generally accepted units of length, the results of measurements of the coordinate in d.p. need to be converted into meters, centimeters, and millimeters. To do this, one needs to apply scale coefficients, which are calculated according to the size of the image. Such a scale coefficient indicates the distance in mm between adjacent discrete points.

5. Apply a scaling coefficient to obtain current coordinates in mm, cm, m.

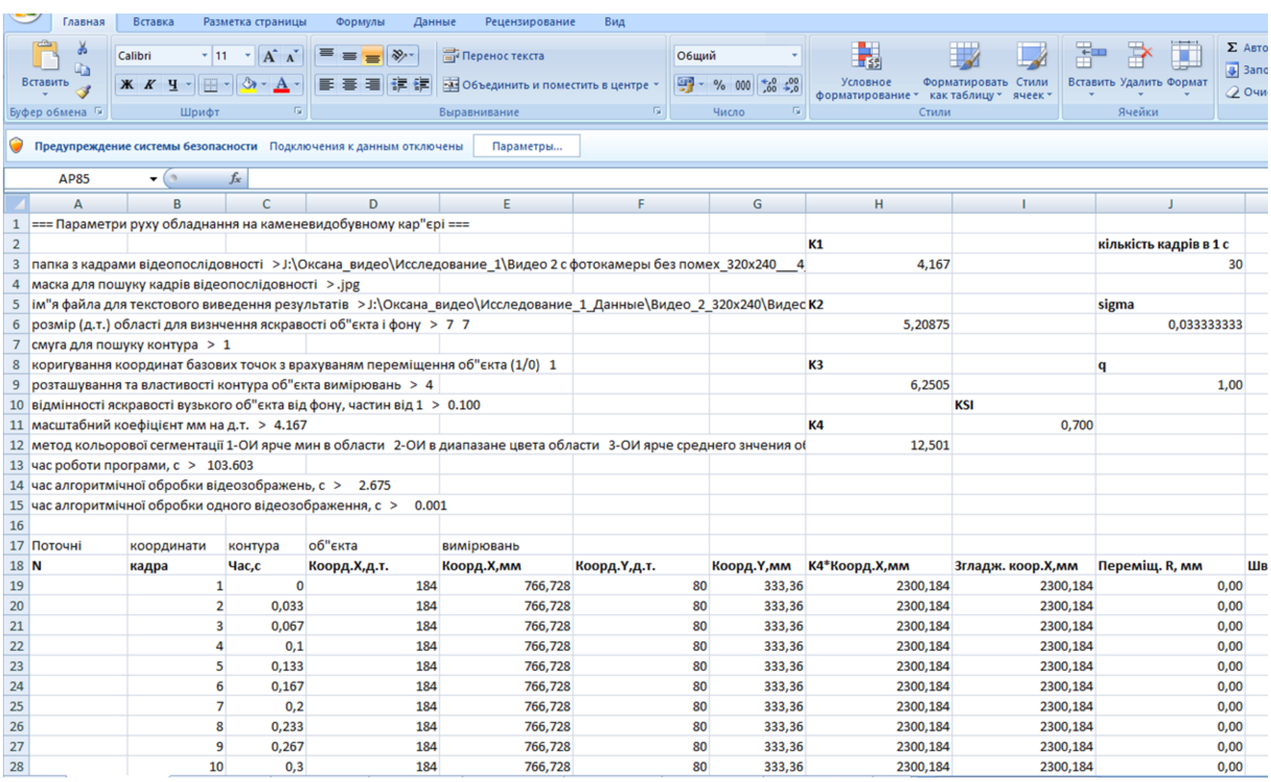
6. Calculate the movement, speed, acceleration of objects based on the geometrical parameters, current coordinates of objects, and numerical methods of differentiation, or alternative software-algorithmic computational methods.

7. Apply software-algorithmic methods for processing measurement results to increase the accuracy of determining the parameters of motion of objects, for example, exponential smoothing procedures containing measured motion parameters. It is also possible to use the complexation (combination) according to the scheme of filtration of measuring information from a video sequence and from an accelerometer mounted on technological equipment.

8. Visualize the results of determining the parameters of object movement in numerical and graphical form.

The measured values and results of numerical calculations in the information-measuring system can be stored in the form of a sequence of records and general informatization about the conditions of measurement and the characteristics of the formed video sequence (Fig. 4).

With this form of storage of measuring information, each database entry corresponds to one frame of a video sequence and the values of motion parameters at a certain point in time obtained on its basis.



	A	B	C	D	E	F	G	H	I	J
1	=== Параметри руху обладнання на каменевидобувному кар"єрі ===									
2								K1		кількість кадрів в 1 с
3	папка з кадрами відеопослідовності >J:\Оксана_видео\Исследование_1\Видео 2 с фотокамеры без помех_320x240___4							4,167		30
4	маска для пошуку кадрів відеопослідовності >.jpg									
5	ім"я файла для текстового виведення результатів >J:\Оксана_видео\Исследование_1_Данные\Видео_2_320x240\Видес							K2		sigma
6	розмір (д.т.) області для визнчення яскравості об"єкта і фону > 7 7							5,20875		0,033333333
7	смуга для пошуку контура > 1									
8	коригування координат базових точок з врахуванням переміщення об"єкта (1/0) 1							K3		q
9	розташування та властивості контура об"єкта вимірювань > 4							6,2505		1,00
10	відмінності яскравості вузького об"єкта від фону, частин від 1 > 0.100								KSI	
11	масштабний коефіцієнт мм на д.т. > 4.167							K4	0,700	
12	метод кольорової сегментації 1-ОИ ярче мин в области 2-ОИ в диапазане цвета области 3-ОИ ярче среднего знчения об							12,501		
13	час роботи програми, с > 103.603									
14	час алгоритмічної обробки відеозображень, с > 2.675									
15	час алгоритмічної обробки одного відеозображення, с > 0.001									
16										
17	Поточні	координати	контура	об"єкта	вимірювань					
18	N	кадра	Час,с	Коорд.X,д.т.	Коорд.X,мм	Коорд.Y,д.т.	Коорд.Y,мм	K4*Коорд.X,мм	Згладж. коор.X,мм	Переміщ. R, мм
19		1	0	184	766,728	80	333,36	2300,184	2300,184	0,00
20		2	0,033	184	766,728	80	333,36	2300,184	2300,184	0,00
21		3	0,067	184	766,728	80	333,36	2300,184	2300,184	0,00
22		4	0,1	184	766,728	80	333,36	2300,184	2300,184	0,00
23		5	0,133	184	766,728	80	333,36	2300,184	2300,184	0,00
24		6	0,167	184	766,728	80	333,36	2300,184	2300,184	0,00
25		7	0,2	184	766,728	80	333,36	2300,184	2300,184	0,00
26		8	0,233	184	766,728	80	333,36	2300,184	2300,184	0,00
27		9	0,267	184	766,728	80	333,36	2300,184	2300,184	0,00
28		10	0,3	184	766,728	80	333,36	2300,184	2300,184	0,00

Fig. 4. The window for displaying the measured and calculated values of motion parameters in a text format

5. 3. Experimental study of the information-measuring system and the method for determining parameters of objects' movements

The proposed structural scheme of the information-measuring system and the method for determining the parameters of the movement were tested and tested during the experimental study. The practical task of measuring and controlling the movement of technological equipment in the quarry for the extraction of block natural stone [4, 10] was solved. The separation of stone blocks from the array of rocks of the deposit is carried out with the help of a diamond-rope installation. An important condition for obtaining high-quality articles is to ensure the stability of displacement parameters and the speed of both the installation and the diamond rope. The existing means of indirect control of motion parameters is determining the current of the main drive of the installation. Under the conditions of the technological process, it is desirable to control instantaneous fluctuations in the rate of sawing and the magnitude of movements, which can lead to deviations in the geometric shape of the surface of the blocks, an increase in waste in the subsequent processing, and a decrease in the quality of blocks.

The use of the designed system for measuring the parameters of objects' movements with an adaptive inter-frame interval of a video sequence could lead to the following useful consequences:

– optimization of technological process parameters;

– improving the quality of blocks and production technology;

– dynamic control over technological process parameters.

An example of the obtained video sequence with measuring information about the parameters of movement of the diamond-rope unit is shown in Fig. 5.

The resulting video sequence is divided into frames of 1,280×1,024 d. p., the frequency is 30 frames per second, the total length of the video sequence was 1 minute 18 sec.

Based on frames of 1,280×1,024 d. p., we also formed three sequences of frames of 320×240 d. p., 640×480 d. p., 1,024×576 d. p. Such dimensions in d. p. correspond to the typical standard values of videos and images processed and visualized by means of information and computer technologies.

Fig. 5. Video sequence with measuring information about motion parameters

We determined the current coordinates of the diamond rope unit for calculating the parameters of movement, in this case, in three different ways:

1. Measuring the current coordinates of the object's path in one fixed line for each frame.

2. Averaging the results of measurements of the current coordinates of the object's contour in n=30 adjacent lines.

3. Averaging the results of measurements of the current coordinates of the object's contour in n=100 adjacent lines.

4. Measuring the coordinates of the center of masses of the object.

Smoothing the coordinate and speed of the movement involved exponential smoothing; the smoothing coefficient in our case is ξ=0.7.

In the above results of the experimental study, we show only the horizontal coordinate because the movement of the diamond-rope installation is executed horizontally.

With the greater expansion, as a reference, we choose to average the results of measurements of the current coordinates of the object's path in n=100 adjacent rows. With a smaller expansion, as a reference, we choose to average the results of measurements of the current coordinates of the object's contour in n=30 adjacent rows.

Measurements take place in real time, so one needs to reduce the amount of computational information.

Real-time images also have lighting and dust interference.

The purpose of our experimental study was to obtain the size of frames in a video sequence and to devise a method for determining the current coordinates, providing an acceptable accuracy of measurements of motion parameters. It is also necessary to take into consideration the need to determine the parameters of movement in real time, which predetermines a possible decrease in the number of computational operations in the processing of video sequence frames. This can be implemented by reducing the size of frames; selecting one of the first three ways to determine the current coordinates; using an adaptive inter-frame interval of the video sequence.

To assess errors, the reference values of the current coordinates were obtained for the center of mass of the object from a video sequence of 1,280×1,024 d. p. This is the most accurate and, at the same time, most time-consuming option for determining coordinates in computational terms, compared to other techniques affected by errors in the discreteness of coordinates in a digital image (Fig. 6).

It was experimentally established that the distribution of errors in determining the current coordinates of the object (the body of a diamond-rope installation) is approaching normal (Fig. 7).

Therefore, generally known valuation approaches based on the mean square value and interval estimates can be applied to this error.

Based on the software-algorithmic processing of the results of measurements of current coordinates, assessments of their errors were obtained: the maximum error value (Fig. 8), the systematic and random component of this error (Fig. 9).

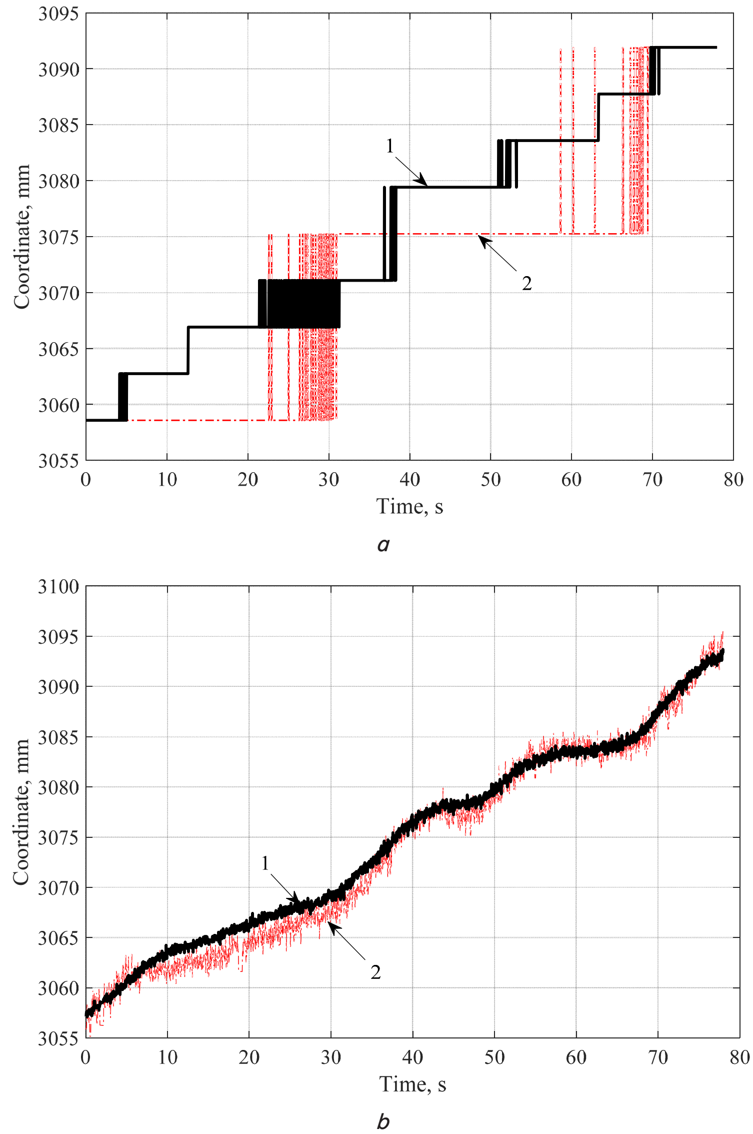


Fig. 6. The results of measurements of the current coordinates of the object (the body of a diamond-rope installation): *a* – measurement of the coordinates of the object's contour in one line of the image; *b* – measurement of coordinates of the center of masses of the object; 1 – image size, 1,280×1,024 d. p.; 2 – image size, 320×240 d. p.

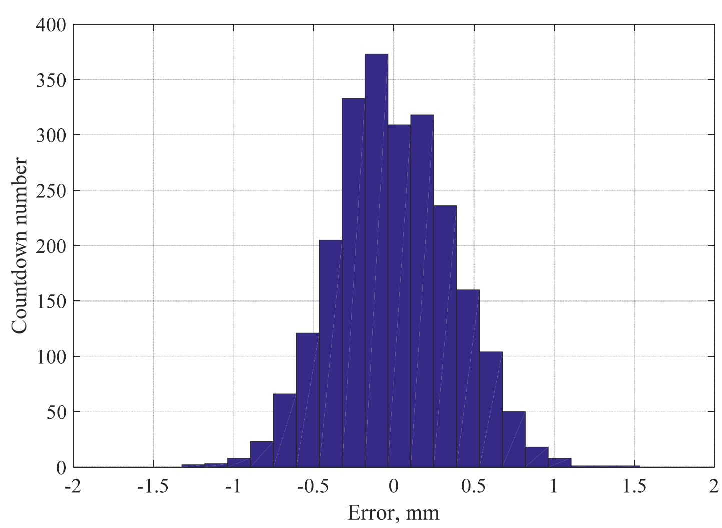


Fig. 7. Distribution histogram of a random error in measuring the coordinates (image size, 1,280×1,024 d. p., averaging the coordinate of the object's path in 100 adjacent rows)

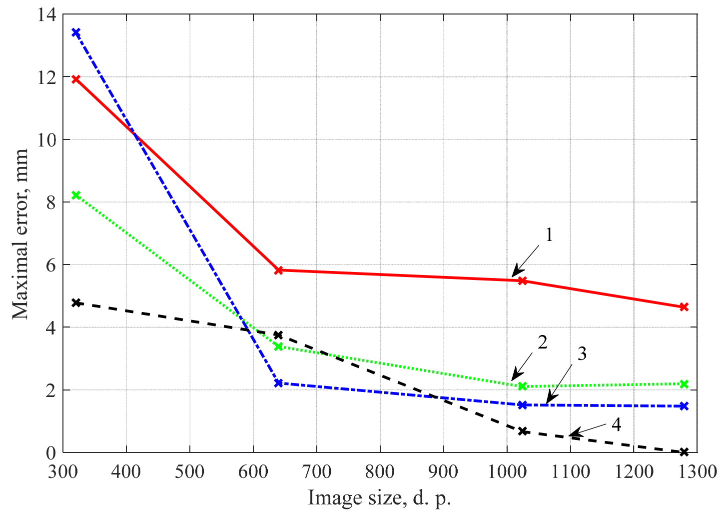
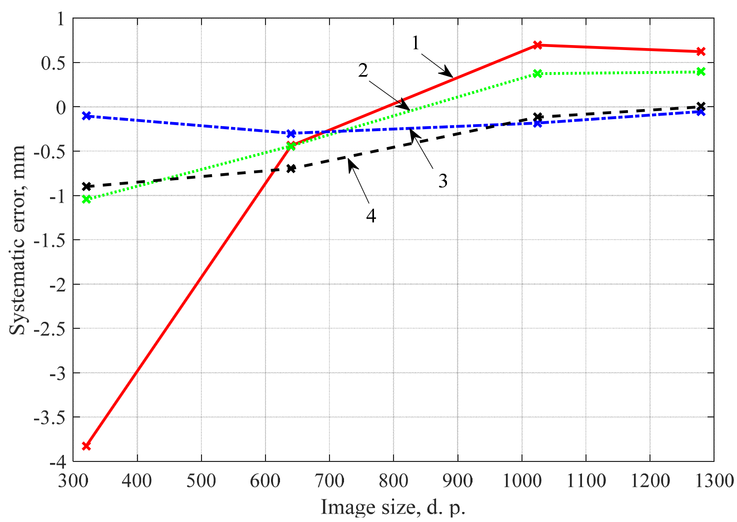
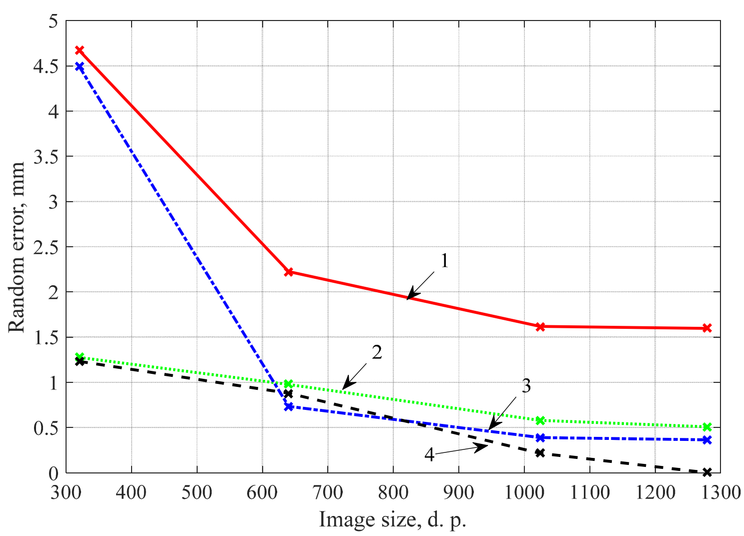


Fig. 8. Maximum error value in measuring the coordinates of an object (the body of a diamond-rope installation): 1 — measurement of the coordinate of the object's contour in one line of the image; 2 — averaging the coordinate of the path in 30 adjacent lines; 3 — averaging the coordinate of the contour in 100 adjacent lines; 4 — measurement of the coordinates of the center of masses of the object



a



b

Fig. 9. Errors in measuring the coordinates of an object (the body of a diamond-rope installation: *a* — systematic component; *b* — random component: 1 — measurement of the coordinate of the object's contour in one line of the image; 2 — averaging the coordinate of the contour in 30 adjacent lines; 3 — averaging the coordinate of the contour in 100 adjacent lines; 4 — measuring the coordinate of the mass center of the object

Next, the speed of movement of the object (the body of a diamond-rope unit) was calculated according to the numerical integration procedure in line with (1), (2); the speed error assessment was obtained (Fig. 10, *a*). In addition, exponential smoothing was applied to the object's velocity countdowns and error assessments were obtained (Fig. 10, *b*).

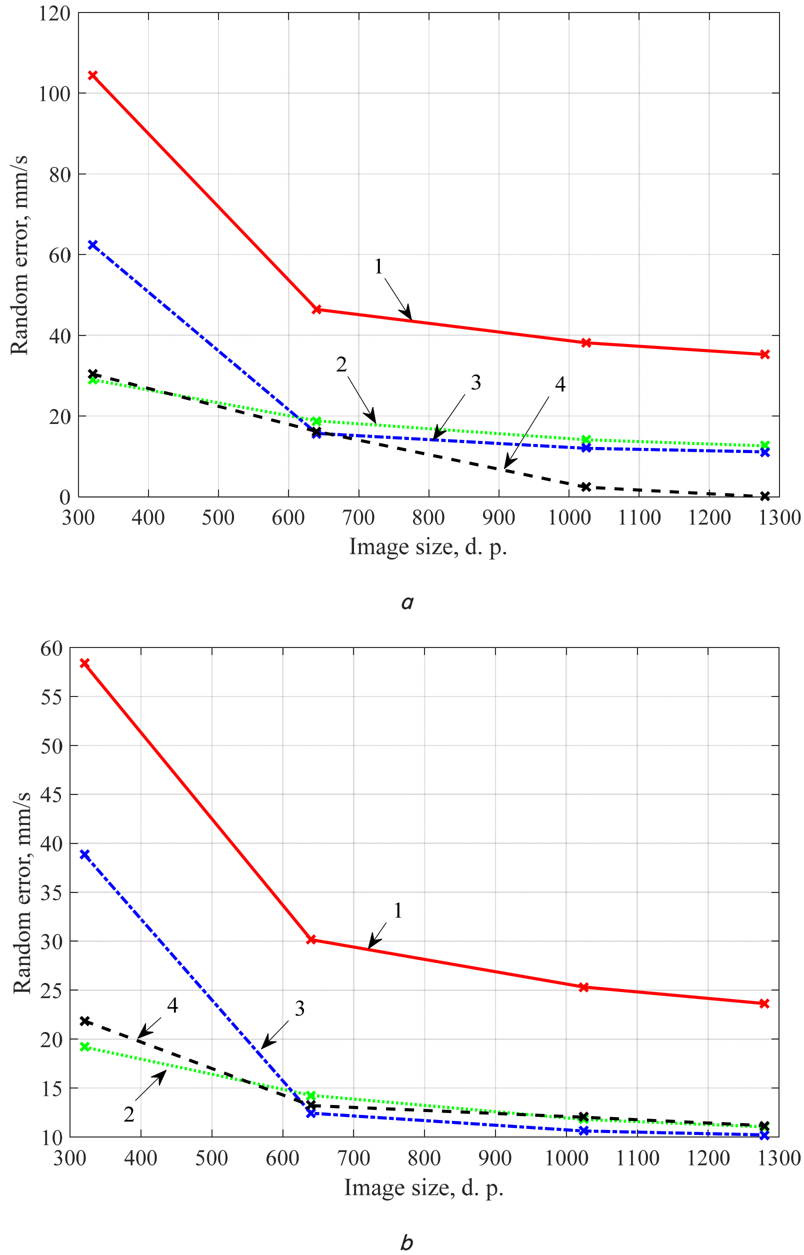


Fig. 10. Random error of speed measurement results: *a* – based on numerical differentiation; *b* – based on exponential smoothing: 1 – measuring the coordinates of the object's path in one line of the image; 2 – averaging the coordinate of the path in 30 adjacent lines; 3 – averaging the coordinate of the contour in 100 adjacent lines; 4 – measurement of the coordinates of the center of masses of the object

The obtained data on errors in the results of measurements of motion parameters were stored in the information-measuring system. They were subsequently used to select adaptive parameters for a time video sequence.

5. 4. Selecting adaptive parameters for a time video sequence and estimating the accuracy of determining the parameters of object movement

Based on the results of our experimental study of the information-measuring system and motion parameters measurement errors, it is necessary to define the adaptive parameters for time video sequences, providing the required accuracy and speed of these measurements in practical tasks.

In the experimental study, the adaptive inter-frame interval of a video sequence was adjusted in accordance with the speed value at the interval of the observation of the movement of a diamond-rope unit.

Averaging the coordinates of a path in adjacent rows and exponentially smoothing the speed countdowns improve the accuracy of determining the motion parameters of objects.

Our experimental study has revealed several features in the application of the information-measuring system and methods for processing measuring information. The research was carried out using a practical example of determining and controlling the parameters of movement of a diamond-rope installation separating blocks of natural stone from the rock massif of the deposit.

An important issue in the experimental study is to determine the parameters of images in a video sequence (the size at discrete points and an inter-frame interval). One also needs to choose a procedure for measuring the current coordinates of the object, which are used further to calculate the parameters of movement in real time. At the same time, conflicting requirements are to ensure the speed of measurement of motion parameters in real time and ensure high accuracy of the results of these measurements.

Based on the experimental data, we see that the simplest option is to determine the current coordinates of the path in one fixed line of a video sequence's frames. However, due to the influence of the discrete nature of digital images, the accuracy of determining the current coordinates is insufficient. The systematic error is up to 4.8 mm, the rms value of the random error is up to 4.7 mm, the maximum error value is up to 13.6 mm at the size of images of 320×240 d. p. (Fig. 8, 9). Calculating the coordinates of the mass center is a complex computational procedure that gives much better accuracy of measuring the coordinates of an object but it cannot be performed in real time.

Therefore, it is advisable to average the coordinates of the object's path in adjacent lines of each frame of the video sequence. The number of 30 and 100 averaged rows produces an almost similar result in accuracy. In terms of improving the speed of determining the current coordinates and motion parameters in real time, it is best to average the coordinates of the path in 30 adjacent lines at the number of

30 frames per second in the video sequence. In this case, subject to compensation for the systematic component, the error in determining the current coordinates is ±1.2 mm with a confidence probability of 0.95 for the frames of a video sequence of 1,024×576 d. p. (Fig. 8, 9). Given the default block size (1,500...2,000) mm and the corresponding displacement range of the diamond-rope unit, this is quite an acceptable result in terms of the accuracy and speed in determining the parameters of objects' movements.

When applying software-algorithmic procedures of exponential smoothing to the sequence of values of current coordinates, there was no significant increase in the accuracy of these values. This is due to the already existing averaging of the coordinates of the path in adjacent rows, which reduces the effect of random failures on the results of measurements.

In contrast, exponential smoothing of the current values of the speed of the object (the body of a diamond-rope installation) turned out to be effective. The speed calculation was carried out according to the methods of numerical differentiation for the countdown of the current coordinates obtained from a time video sequence, formed at a frequency of 30 frames per second. Applying the software-algorithmic procedures of exponential smoothing ensured an increase in the accuracy of determining the speed of an object, by (1.4...1.6) times, at the dimensions of a video sequence frames of 640×480 d. p. and 1,024×576 d. p. (Fig. 10).

6. Discussion of results of studying the method and system to determine the parameters of objects' movements

Our research results testify to solving successfully the task of devising a method for measuring motion parameters using time video sequences. The structural diagram of the information-measuring system supports the implementation of the devised method and the adaptation of video sequence parameters to the conditions of measurement.

At the same time, the accuracy and performance indicators of the devised method and the system for determining the parameters of movement are explained by the influence of the following factors:

– software and algorithmic methods used for the processing of measured video information;

– the structure and characteristics of the information-measurement system's units;

– errors inherent in the components of the measuring channel, which forms and transforms the measuring video information about the parameters of objects' movements.

An important feature of the proposed method for determining the parameters of movement is the fundamental possibility of using structural methods to increase accuracy, namely the use of two measuring channels in the construction of an information-measuring system. Unlike existing measurement circuit complexation schemes, one or both channels can use contactless measurements of current coordinates and motion parameters of objects using digital video cameras and time video sequences. In accordance with this, the structural scheme of the system was designed, which, in combination, provides the choice of parameters of a time video sequence in accordance with the current values of the parameters of movement of industrial objects and the conditions for conducting measurements (Fig. 2, 3).

In addition, an important feature of our results in comparison with the existing ones is the use of software-algorithmic methods for improving accuracy, provided that measurements are performed in real time. These are using contour coordinate processing in adjacent image lines, exponentially smoothing the calculated motion parameter values according to (5), and adaptively adjusting the time-based video sequence settings.

The simplest computational and fast-acting methods of numerical differentiation do not take into consideration the presence of a discrete error in the measured coordinate counts. Therefore, averaging the coordinates of the object's path in adjacent lines of each video frame has been applied. To increase the accuracy of measurements, exponential smoothing of coordinates and motion parameters was also applied, as well as adaptive parameters of a time video sequence based on a priori information about the movement of the measured object. These methods make it possible to reduce dynamic errors when changing the parameters of motion of objects that are measured and controlled.

The procedures for the formation and processing of time video sequences (the second task of our research) ensure obtaining measuring information about the parameters of objects' movements. However, it is necessary to note the limitations inherent in this study. Significant differences in brightness and/or color between the surface of the measured object and the background of the image must be ensured. That is due to the further distribution of the image to the area of the object and background and determining the current coordinates of the object's contour in the software-algorithmic support to the information-measuring system. If such a difference is not previously available, then it is possible to apply a contrast mark on the surface of the measurement rotation before measuring its movement parameters.

It is also necessary to ensure the optical interaction of the device for the formation of digital images with the object of measurement.

We have experimentally tested the software-algorithmic methods of accuracy improvement, provided that measurements are performed in real time. This is the use of the coordinate processing of the path in adjacent lines of the image (Fig. 7–9), the exponential smoothing of the calculated values of motion parameters according to (5), and the adaptive adjustment of a time video sequence's parameters.

At the same time, conflicting requirements are to ensure the speed of measurement of motion parameters in real time and ensure high accuracy of the results of these measurements.

During our experimental study, the simplest methods of numerical differentiation were used to calculate the speed of a diamond-rope unit. However, these methods do not take into consideration the presence of error in the measured coordinate counts. The most significant error is the error of discreteness for one coordinate of the path (Fig. 6, *a*), determined by the resolution of the formed digital image. Calculating the coordinates of the center of masses is a complex computational procedure that eliminates the effect of discrete error and gives much better accuracy of measuring the coordinates of an object (Fig. 6, *b*). However, such a procedure cannot be performed in real time.

Therefore, an effective measure was the averaging of the coordinates of the object's path in adjacent lines of each frame of the video sequence. It is established that the best is to average the coordinates of the path in 30 adjacent lines at the number of 30 frames per second in a video sequence. If the systematic component is compensated, the error in determining the current coordinates is ±1.2 mm with a confidence probability of 0.95 (Fig. 9, *b*).

The exponential smoothing of the time sequence of coordinates and motion parameters was used to increase the accuracy of measurements. Unlike smoothing the sequence of current coordinates, the exponential smoothing of the current values of the speed of the body of a diamond-rope installation turned out to be effective; the accuracy increased by (1.4...1.6) times (Fig. 10).

Setting the adaptive time video sequence parameters based on a priori information about the movement of the measured object makes it possible to reduce the inter-frame interval and the interval between adjacent countdowns of the measuring information being processed. As a result, our results with lower dynamic errors describe changes in the parameters of motion of objects that are measured and controlled.

The specified structural and algorithmic methods ensure taking into consideration the existing patterns of objects' movements and reducing the errors when measuring motion parameters.

A deterrent and limitation for the development of software and algorithmic methods of video sequence processing is the use of microprocessor systems and microcontrollers, rather than a powerful computer. This is due to the influence of adverse factors on the information and measurement system under working conditions of measurements during production. Overcoming this limitation implies the use of specialized computing tools and chips of microcontrollers designed to process digital images in a parallel computing mode.

As a disadvantage of this study, we can note the setting of the adaptive parameters of a time video sequence immediately before the start of measurements based on a priori information about the movement of the measured object. Therefore, for further research, an important task is the practical implementation in the software-algorithmic support of procedures for adapting the video sequence parameters directly during real-time measurements. It should be noted that achieving this would require the derivation of mathematical formulas to assess the parameters of movement with variable steps between the countdowns of the current coordinates of objects.

The area of further development of our experimental research is also the use of two channels for acquiring measuring information about the parameters of movement of a diamond-rope installation and other objects of production purpose. In this case, it will be necessary to theoretically determine the transfer functions of two measuring channels according to (7) and Fig. 1 in the information-measurement system.

7. Conclusions

1. We have proposed a measuring method and a structural scheme of the information-measuring system for determining the parameters of objects' movements. The objects measured and controlled can be a variety of industrial articles and parts of production equipment used in their manufacture. A carrier of the measuring information about the current geometrical parameters and motion parameters of objects is a time video sequence containing images of these objects. The parameters of the video sequence and individual images are adjusted in accordance with the current values of motion parameters and the requirements for measuring procedures. Accordingly, the parameters of the movement of such objects characterize the course of the technological process, compliance with the requirements of regulatory documents, while the operational control over motion parameters in real time ensures an improvement in the quality of industrial articles.

2. To acquire measuring information about the parameters of objects' movements, a time video sequence is gradually processed by the software-algorithmic support to the information-measuring system. A video sequence is formed that contains significant differences in brightness and/or color between the subject and background. It is then split into individual frames according to the current adaptive settings and the frames measure the geometry and current coordinates of the objects. This is performed by averaging the results of measurements of the current coordinates of the object's path in 30 adjacent lines, in which an image of the object is available based on the results of segmentation of the frame to the measured object and background. In addition, a scaling coefficient is additionally used to obtain current coordinates not in discrete points of the image but in generally accepted units of length. The movement, speed, acceleration of objects based on current coordinates of objects and numerical methods of differentiation and software-algorithmic methods of increasing the accuracy of determining movement parameters are calculated.

3. The experimental study was carried out using a practical example of determining and controlling the parameters of movement of a diamond-rope installation separating blocks of natural stone from an array of rocks of the deposit. To improve the accuracy of determining the parameters of objects' movements, it is recommended to use structural methods (the use of two measuring channels in the construction of an information-measuring system). It is also necessary to apply the software-algorithmic methods for processing the measuring information (averaging the coordinates of the path in adjacent lines of the image, exponential smoothing of the calculated values of motion parameters, adaptive adjustment of time video sequence parameters).

4. Subject to compensation for the systematic component, the error in determining the current coordinates is ±1.2 mm with a confidence probability of 0.95 for the frames of a video sequence of 1,024×576 d. p. Given the typical block size of (1,500...2,000) mm and the corresponding displacement range of a diamond-rope unit, this is quite an acceptable result in terms of the accuracy and speed of determining the parameters of objects' movements. The speed calculation was carried out according to the methods of numerical differentiation for the countdown of the current coordinates obtained from a time video sequence, formed at a frequency of 30 frames per second. By applying the software-algorithmic procedures of exponential smoothing, an increase in the accuracy in determining the speed of an object is achieved, by (1.4...1.6) times, at the dimensions of the video sequence frames of

640×480 d. p. and 1,024×576 d. p. The area of further experimental research can be to use two channels for acquiring measuring information about the parameters of movement of a diamond-rope installation and other objects of production purpose.

To improve the accuracy of determining the parameters of objects' movements, it is recommended to use structural methods (the use of two measuring channels in the construction of an information-measuring system). It is also necessary to apply the software-algorithmic methods for processing measuring information (averaging the coordinates of the path in adjacent lines of the image, exponential smoothing of the calculated values of motion parameters, adaptive adjustment of time video sequence parameters).

Our experimental results indicate the possibility of the practical application of the designed information-measuring system and the proposed software-algorithmic methods for processing measurement results.

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