MEASUREMENT OF THE GEOMETRIC PARAMETERS OF OBJECTS BASED ON COMPUTERIZED PROCESSING OF VIDEOIMAGES

Podchashinskiy Yu., Syvak O.

INTRODUCTION

The urgent direction of modern instrument-making industry development is the development of new high-speed precision tools for measuring and controlling the mechanical quantities for industrial enterprises. In the framework of this direction, the possibility of creating a system for measuring geometric parameters of objects (for example, industrial products that are beeing manufactured) have been investigated. For increasing accuracy and speed, expanding the functional abilities of the created measuring system, modern methods of forming and computerized processing of video images of objects of measurement have been used.

The traditional way of improving the metrological characteristics of measuring instruments of mechanical quantities is design as well as technology improvment of manufacturing of these instruments. But the possibilities of such an approach are almost exhausted at the moment.

The modern method for measuring mechanical quantities is the formation and algorithmic processing of signals, which contain useful information about the objects of measurement[1, 2, 3, 4]. In this regard, the perspective direction of improving the means of measuring mechanical quantities is the use of the capabilities of modern information and computer technologies for the formation and computerized processing of signals of measurement information (including video images) as wel as the results of measurements[5, 6, 7, 8, 9].

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[1] Мейдза Ф. Электронные измерительные приборы и методы измерений: пер. с англ. Москва, 1990. 535 с.

[2] Blanchet G. Digital Signal and Image Processing Using Matlab. London, 2006. 764 p.

[3] Гутников В.С. Фильтрация измерительных сигналов. Ленинград, 1990. 192 с.

[4] Власенко В.А., Шкодин О.И. Микропроцессорные системы неразрушающего контроля качества изделий электронной техники. Киев, 1990. 144 с.

[5] Бортник Г.Г., Кичак В.М. Цифрова обробка сигналів: навч. посібник. Вінниця: ВНТУ, 2006. 167 с.

On the basis of computerized processing of video images the geometric parameters (linear dimensions, angles, perimeter) of the external contour of objects of measuring, as well as geometric parameters (area, center of mass, linear dimensions, angular position, coefficients of geometric form) of structural elements of surface of objects of measuring as a flat figure in the plane of a two-dimensional image can be measured. The results of mentioned measurements can be used to control the quality of industrial products, to investigate various technical objects, to evaluate and control the geometric parameters of objects in environmental studies.

The conducted research is directed on the solving of the actual scientific problem, which consists in increase of accuracy and speed, expansion of functional possibilities of means of measurement of mechanical quantities. The suggested measuring system can be used to determine the geometrical parameters of various technical objects and industrial products. Measurement of geometric parameters of objects is carried out on the basis of the use of computer-aided processing of video images.

1. Geometric parameters of objects that can be defined by using their video image

The surface of the objects of measurement can be characterized by a two-dimensional function $f_0(x, y)$, where x and y are the spatial coordinates in the plane of this surface, and the value of the function f_0 for each pair of coordinates (x, y) is the measure of the brightness of the objects of measurement surface at the point with these coordinates. The use of two spatial coordinates is due to the fact that a digital image is formed for measurements, which is a two-dimensional projection of the original three-dimensional object of measurements. Therefore, we will consider

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[6] Наконечний А.Й., Наконечний Р.А., Павлиш В.А. Цифрова обробка сигналів: навч. посібник. Львів: НУ «Львівська політехніка, 2010. 368 с.

[7] Kehtarnavaz N., Gamadia M. Real-Time Image and Video Processing: From Research to Reality. New York, 2006. 107 p.

[8] Mann S. Intelligent Image Processing. New York, 2002. 359 p.

[9] Petrou M., Bosdogianni P. Image Processing. The Fundamentals. New York, 1999. 347 p.

objects of measurement as a flat geometric figure, which is located in the plane of the video image.

The surface of the product is located in the field of view of the optical system of the device of video image formation (digital video camera) and projected by this system in the plane of the initial video image $f_0(x_{\text{VI}}, y_{\text{VI}})$, where x_{VI} and y_{VI} − the spatial coordinates in the plane of the original video. This plane coincides with the photosensitive surface of the converter “light-signal” in the digital video camera.

While forming video images, geometric errors[10] arise due to: the distortion of the optical system; non-perpendicularity of the plane surface of the objects of measurement as well as the optical axis of the digital video camera; the differences in the shape of the surface of the objects of measurement from the plane. As a result, on the surface of the converter “light-signal” we obtain a video $f_{\text{os}}(x_{\text{vi}}, y_{\text{vi}})$ with geometric errors. It is also necessary to take into account the presence of dynamic errors of video images in the optical system that are characterized by the point scattering function in the “light-signal” converter and electronic circuits characterized by inertial properties at rapid changes in the amplitude of the video signal in the area of the contours of the objects of measurement. In addition, all these digital video camera blocks add random errors $\xi(x_{\text{VI}}, y_{\text{VI}})$ to the video image. As a result, we obtain video image $f_{\text{D}}(x_{\text{VI}}, y_{\text{VI}})$ that contain geometric and dynamic errors as well as video image at the output of a digital camera $f_{\text{F}}(x_{\text{VI}}, y_{\text{VI}}) = f_{\text{D}}(x_{\text{VI}}, y_{\text{VI}}) + \xi(x_{\text{VI}}, y_{\text{VI}})$ with random errors.

Converters “light-signal” of modern digital cameras represent a matrix of photosensitive elements. Such a matrix, together with an analog-to-digital video converter, forms a digital video image $f_{\text{F}}(n,m)$, which is a two-dimensional array (matrix) of reference brightness, whose values are quantized by amplitude. In this case: n,m − the ordinal numbers (indices) of the discrete countdown of the amplitude of the video signal in the rows and columns of the digital video image, $n \in \overline{1,N}$,

[10] Форсайт Д., Понс Ж. Компьютерное зрение. Современный подход. Москва, 2004. 928 с.

$m \in \overline{1,M}$; N, M − the number of discrete countdowns of video signal amplitudes in the rows and columns of the digital video image of the product, which determines the size of the digital video image at discrete points (d.p.). A digital video image $f_F(n,m)$ is a video image representation in the digital form $f_F(x_{VI}, y_{VI})$ on the output of a digital video camera.

The digital video image $f_F(n,m)$ from the output of the digital video camera is transferred to the computer. For an achromatic surface of objects of measurements there is enough of one half-tone digital video image $f_F(n,m)$ that characterizes the brightness of the points of this surface. For the chromatic surface of the objects of measurement, a color digital video image is formed containing 3 channels (3 digital monochrome video images) and characterizes the brightness and color of the surface of the object according by a certain colorimetric system. The most common is the colorimetric system RGB (R, G and B – respectively, the red, green and blue colors, and brightness $Y = 0{,}30R + 0{,}59G + 0{,}11B$ [11, 12]. All the statements and methods of computerized video image processing are applied to both the half-tonal digital video image $f_F(n,m)$ as well as to each of the channels of color digital video image.

Algorithmic compensation of errors on a digital video image $f_F(n,m)$ is performed in the computer. As a result, we consistently receive digital video images $f_D^*(n,m)$, $f_{os}^*(n,m)$and $f_0^*(n,m)$ that are calculated in the digitized form by video image rating $f_D(x_{VI}, y_{VI})$, $f_{OS}(x_{VI}, y_{VI})$ i $f_0(x_{VI}, y_{VI})$. Taking into account the coefficient of increase of the optical system a digital video image $f_0^*(n,m)$ is also a calculated rating of a two-dimensional function $f_0(x,y)$ that characterizes the surface of objects of measurement.

Elements (dots) of digital video image $f_0^*(n,m)$ with indexes (n,m) characterize the brightness of the original video image $f_0(x_{VI}, y_{VI})$ with

[11] Претт У. Цифровая обработка изображений. Москва, 1982. 792 с.
[12] Гонсалес Р., Вудс Р. Цифровая обработка изображений. Москва, 2005. 1072 с.

coordinates[13, 14] $x_{\text{VI}} = n \cdot \delta_{x1}$, $y_{\text{VI}} = m \cdot \delta_{y1}$, where δ_{x1} and δ_{y1} are the distance horizontally and vertically between the centers of the neighboring light-sensitive elements of the "light-signal" converter.

If the coefficient of increase of the optical system k_{mos}[15] is known then $x = x_{\text{VI}} / k_{\text{mos}} = n \cdot \delta_x$, $y = y_{\text{VI}} / k_{\text{mos}} = m \cdot \delta_y$, where δ_x and δ_y are the step of the discreteness of the spatial coordinates x and y in the plane of the surface of the objects of measurement, which corresponds to a distance of 1 d.p. on a digital video image $f_0(n,m)$.

To measure the geometric parameters digital video image $f_0^*(n,m)$ is used. Before measuring the geometric parameters in this video image, the area Q_{OM} that belongs to the object of measurements is selected. This is done by distributing the video image to the objects of measurement as well as to the background or by selecting the contours of the objects with the furhter construction of the areas belonging to these objects.

The digital video after the selection of the object of measurement has the form[16, 17]:

$$f_{0\,\text{SEGM}}^*(n,m) = \begin{cases} 1, & \text{if } f_0^*(n,m) \in Q_{\text{OM}}, \\ 0, & \text{if } f_0^*(n,m) \notin Q_{\text{OM}}. \end{cases} \tag{1}$$

The basis of the process of geometric parameters measuring is the equation of measurement and the error equation[18]. For the coordinates of the points on the surface of the objects of measurement, we have the following equations of measurement:

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[13] Jeahne B. Practical Handbook on Image Processing for Scientic and Technical Applications. Boca Raton, 2004. 571 p.

[14] Форсайт Д., Понс Ж. Компьютерное зрение. Современный подход. Москва, 2004. 928 с.

[15] Форсайт Д., Понс Ж. Компьютерное зрение. Современный подход. Москва, 2004. 928 с.

[16] Шапиро Л., Стокман Дж. Компьютерное зрение. Москва, 2006. 752 с.

[17] Форсайт Д., Понс Ж. Компьютерное зрение. Современный подход. Москва, 2004. 928 с.

[18] Грановский В.А., Сирая Т.Н. Методы обработки экспериментальных данных при измерениях. Ленинград, 1990. 288 с.

$$x[\text{d.p.}] = q_x \cdot [1\text{d.p.}],\ y[d.\text{p.}] = q_y \cdot [1\text{d.p.}],$$
$$x[\text{мм}] = k_{\text{m}x} \cdot x[\text{d.p.}],\ y[\text{мм}] = k_{\text{m}y} \cdot y[\text{d.p.}], \quad (2)$$

where q_x, q_y are indices (ordinal numbers in a row and a column) of a digital countdown of a two-dimensional digital video image that corresponds to the measured point of the object; $[1\text{d.p.}]$ is the distance horizontally and vertically between two discrete countdowns in the plane of the digital video image; $k_{\text{m}x}[\text{мм/d.p.}]$, $k_{\text{m}y}[\text{мм/d.p.}]$ are scale coeficients for converting the coordinate values at discrete points (d.p.) of the video image to the value in millimeters, these coefficients are determined by analytical calculation or by experimental research of a video image of a tested object of measurement with known geometric sizes.

Equations (2) take into account the fact that digital video of objects of measurement is a matrix whose elements characterize the brightness and color of the corresponding points of these objects. When processing video images directly determine the coordinates of points as the indexes of the corresponding elements of the matrix. This is due to the use of intermediate calculations of the coordinates and distances of the unit in 1 d.t. But the final results of measurements of geometric parameters of objects are given in units of SI system, that is, in meters or millimeters.

The equation of error measurement of the coordinates of the points of measurement objects has the form:

$$x^*[d.\text{p.}] = x + \Delta_{x*} = \left(q_x + \Delta_{qx}\right) \cdot \left([x] + \Delta_{[x]}\right),$$
$$y^*[\text{d.p.}] = y + \Delta_{y*} = \left(q_y + \Delta_{qy}\right) \cdot \left([y] + \Delta_{[y]}\right),$$

where Δ_{x*}, Δ_{y*} are general errors of results x^*, y^* of measuring coordinates; Δ_{qx}, Δ_{qy} are errors in finding numerical values of coordinates (including: random, dynamic and geometric errors of video images encountered in a digital video camera, errors due to discrete nature of digital video images and their transformations and encodings when entered into a computer); $\Delta_{[x]}$, $\Delta_{[y]}$ are errors of reproduction unit of measurements $[x]=[y]=[1\text{d.p.}]$, due to errors of manufacturing of the matrix converter "light signal" in a digital video camera.

The geometric parameters of the objects of measurement are determined by numerical calculations in the computer based on the measured values of the coordinates of the points of measurement objects. For such calculations, the most significant is the transformed error due to the existing errors in the initial data for calculations (coordinates of the points of measurement objects).

Compensation of errors in determining the geometric parameters of objects of measurement is carried out by computerized processing of video images and results of measuring geometric parameters. To refer to such a procedure, the term "algorithmic error compensation" is used.

On a digital video image $f^*_{0\,\text{segm}}(n,m)$ according to the measurement equations (1.2) the coordinates of points with numbers can be directly measured (n_j, m_j), that belong to the object ($j \in \overline{1, N_{\text{OM}}}$, N_{OM} – total number of points belonging to the object). Among all points of the object there are points that belong to its contour and structural elements of its surface.

Numbers of points (n_j, m_j) on the digital video image are calculated according to the measurement equations (2) in the coordinates of the corresponding points (x_j, y_j) on the surface of the objects of measurement, taking into account that $q_x = n_j$, $q_y = m_j$. Coordinates (x_j, y_j) according to the measurement equations, can be expressed in units of length (d.p.) of digital video image or in units of length (meters or millimeters) of the surface of the product. Steps of discretion δ_x and δ_y and scale factors $k_{\text{м}x}$ i $k_{\text{m}y}$ are determined by analytical calculation on the basis of values δ_{x1}, δ_{y1} i k_{mos}. For existing digital cameras, these values may not be known. In this case, the values δ_x, δ_y, $k_{\text{m}x}$ and $k_{\text{m}y}$ are determined on the basis of research of a digital video image of a test object of measurement that has known linear dimensions, predetermined with high accuracy. All other geometric parameters of objects are determined on the basis of algorithmic coordinate processing (n_j, m_j) or (x_j, y_j).

Let's consider the geometric parameters of the objects of measurement that can be determined for each video image by algorithmic processing of the results of measuring point coordinates of the objects of measurements will be considered a flat geometric figure placed in the plane of the video image. The geometric parameters of the objects of measurement can be divided into five groups: the coordinates of the characteristic contours of the object, the linear dimensions and perimeter of the object, various options for determining the area of the object, the morphometric features of the object, the coefficients of the geometric shape of the object[19, 20, 21, 22, 23].

The coordinates of the characteristic contour points of the objects of measurement include:

– a list of all contour points with defined coordinates;

– extreme coordinates of the object (coordinates of the upper, lower, left and right points of the object);

– the coordinates of vertices of a convex polygon in which the object is inscribed;

– the coordinates of the characteristic points of a geometric figure (for example, a rectangle or an ellipse) used to approximate the object.

The linear dimensions of the objects of measurement include its width w and height h, corresponding to the width and height of the rectangle in which this object is inserted. Distance between two points of the object of measurement with

[19] Претт У. Цифровая обработка изображений. Москва, 1982. 792 с.

[20] Гонсалес Р., Вудс Р. Цифровая обработка изображений. Москва, 2005. 1072 с.

[21] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[22] Введение в контурный анализ; приложения к обработке изображений и сигналов / Я.А. Фурман, А.В. Кревецкий, А.К. Передреев и др.; под ред. Я.А. Фурмана. Москва, 2003. 592 с.

[23] Техническое зрение роботов / В.И. Мошкин, А.А. Петров, В.С. Титов, Ю.Г. Якушенков; под общ. ред. Ю.Г. Якушенкова. Москва, 1990. 272 с.

coordinates (x_l, y_l) and (x_j, y_j) equals[24]: $d = \sqrt{(x_j - x_l)^2 + (y_j - y_l)^2}$. Values w, h and d for digital video images can be counted in d.p. or in meters.

The area of the object of measurement can be determined by the following options:

– area of the object $S_{\hat{I}M}$ (the area occupied by this object in a video image);

– the total area of the object that equals to its area with filled holes;

– convex area of the object S_{OM1}, which equals to the area of the convex polygon in which this object is inserted.

The area of the measurement object for a digital video image can be expressed by the corresponding number of points of a digital video image belonging to the object of measurements, or calculated in units of area (m^2).

The morphometric features of the object of measurement, such as a flat figure in the plane of the video image, include the following geometric parameters:

– the center of the mass of the object;

– an equivalent diameter corresponding to the diameter of the circle with an area equal to the area of the object $d_e = \sqrt{4 S_{OM} / \pi}$;

– the length of the maximum axis of inertia of the object as a flat figure;

– length of the minimum axis of inertia of the object as a flat figure;

– the angular position of an object determined by the angle between the horizontal axis of coordinates and the maximum axis of inertia of this object.

Coefficients of the geometric form of the object of measurement, as a fat figure in the plane of the video image include:

– convexity coefficient: $k_c = S_{OM} / S_{OM1}$;

– fill factor: $k_f = S_{OM} / (w \cdot h)$;

– an eccentricity that is determined for an ellipse that has the main moments of inertia the same as an object.

[24] Претт У. Цифровая обработка изображений. Москва, 1982. 792 с.

The generalized version of the geometric parameters of the object of measurement is its moments[25]. Initial moments of the object of order $(\beta+\gamma)$ equal to:

$$m_{\beta\gamma} = \iint\limits_{Q_{\text{OM}}} x^{\beta} y^{\gamma} f_0(x,y)dxdy.$$

The central moments of the order $(\beta+\gamma)$ are determined by the formula:

$$\mu_{\beta\gamma} = \iint\limits_{Q_{\text{OM}}} (x-x_c)^{\beta}(y-y_c)^{\gamma} f_0(x-x_c, y-y_c)dxdy,$$

where x_c, y_c – coordinates of the center of mass of the object of measurements.

The coordinates of the center of mass of the object of measurement are equal[26]:

$$x_c = m_{10}/S_{\text{OM}}, \quad y_c = m_{01}/S_{\text{OM}}.$$

For the video image (1)

$$x_c = \frac{1}{N_{\text{OM}}}\sum_{j=1}^{N_{\text{OM}}} x_j = \frac{\delta_x}{N_{\text{OM}}}\sum_{j=1}^{N_{\text{OM}}} n_j, \quad y_c = \frac{1}{N_{\text{OM}}}\sum_{j=1}^{N_{\text{OM}}} y_j = \frac{\delta_y}{N_{\text{OM}}}\sum_{j=1}^{N_{\text{OM}}} m_j.$$

Important characteristics of the object of measurement, as a flat figure, are its main moments of inertia J_1 i J_2, length of maximum and minimum axis of inertia l_{max} and l_{min} and eccentricity c_{el}. The main moments of inertia are determined in relation to the maximum and minimum axes of inertia of the object of measurement [27, 28]:

$$J_{1,2} = \frac{1}{2}\left(J_x + J_y\right) \pm \sqrt{J_{xy}^2 + \frac{1}{4}\left(J_x - J_y\right)^2},$$

where J_x, J_y, J_{xy} are moments of inertia of the object of measurement in relation to the coordinate axes Ox i Oy, $J_x = \mu_{20}$, $J_y = \mu_{02}$, $J_{xy} = \mu_{11}$.

For the video image (1)

[25] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[26] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[27] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[28] Техническое зрение роботов / В.И. Мошкин, А.А. Петров, В.С. Титов, Ю.Г. Якушенков; под общ. ред. Ю.Г. Якушенкова. Москва, 1990. 272 с.

$$J_x = \frac{1}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (x_j - x_c)^2 = \frac{\delta_x^2}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (n_j - n_c)^2 \text{, де } n_c = \frac{1}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} n_j \text{,}$$

$$J_y = \frac{1}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (y_j - y_c)^2 = \frac{\delta_y^2}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (m_j - m_c)^2 \text{, де } m_c = \frac{1}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} m_j \text{,}$$

$$J_{xy} = \frac{1}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (x_j - x_c)(y_j - y_c) = \frac{\delta_x \delta_y}{N_{\text{OM}}} \sum_{j=1}^{N_{\text{OM}}} (n_j - n_c)(m_j - m_c).$$

The length of the maximum and minimum axes of inertia of the object of measurement, as a plane figure, is determined by the relations[29, 30]:

$$l_{\max} = 2\sqrt{2} \cdot \sqrt{J_x + J_y + 2C_J}\text{,} \quad l_{\min} = 2\sqrt{2} \cdot \sqrt{J_x + J_y - 2C_J}\text{,}$$

де $C_J = \sqrt{J_{xy}^2 + \frac{1}{4}(J_x - J_y)^2}$.

The eccentricity is determined on the basis of the approximation of the measuring object by an ellipse having moments and axis of inertia as in the object of measurements[31, 32]:

$$e_{\text{el}} = \frac{c_{\text{el}}}{a_{\text{el}}} = \frac{2\sqrt{(l_{\max}/2)^2 - (l_{\min}/2)^2}}{l_{\max}}\text{,}$$

where $c_{\text{el}}^2 = a_{\text{el}}^2 - b_{\text{el}}^2$ are half of between the focal length of the ellipse, a_{el} і b_{el} are its half axis.

Based on the moments of inertia of the object of measurement, its angular position in relation to the center of mass can also be determined[33, 34]. This angular

[29] Техническое зрение роботов / В.И. Мошкин, А.А. Петров, В.С. Титов, Ю.Г. Якушенков; под общ. ред. Ю.Г. Якушенкова. Москва, 1990. 272 с.

[30] Taylor G., Kleeman L. Visual Perception and Robotic Manipulation. 3D Object Recognition, Tracking and Hand-Eye Coordination. Berlin, 2006. 230 p.

[31] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[32] Техническое зрение роботов / В.И. Мошкин, А.А. Петров, В.С. Титов, Ю.Г. Якушенков; под общ. ред. Ю.Г. Якушенкова. Москва, 1990. 272 с.

[33] Техническое зрение роботов / В.И. Мошкин, А.А. Петров, В.С. Титов, Ю.Г. Якушенков; под общ. ред. Ю.Г. Якушенкова. Москва, 1990. 272 с.

[34] Taylor G., Kleeman L. Visual Perception and Robotic Manipulation. 3D Object Recognition, Tracking and Hand-Eye Coordination. Berlin, 2006. 230 p.

position is defined as the angle between the axis Ox and the maximum axis of inertia:

$$\alpha = \begin{cases} arctg\dfrac{J_y - J_x + 2C_J}{2J_{xy}}, & J_y > J_x, \\ arctg\dfrac{2J_{xy}}{J_x - J_y + 2C_J}, & J_y < J_x. \end{cases}$$

Another option for determining the angular position of the object of measurement is given in[35]:

$$\alpha = \frac{1}{2} arctg\frac{2\mu_{11}}{\mu_{02} - \mu_{20}} + \lambda, \; \lambda = \begin{cases} 0, & \text{if } \mu_{20} \geq \mu_{02}, \mu_{30} \geq 0, \\ \pi/2, & \text{if } \mu_{20} < \mu_{02}, \mu_{30} \geq 0, \\ \pi, & \text{if } \mu_{20} \geq \mu_{02}, \mu_{30} < 0, \\ 3\pi/2, & \text{if } \mu_{20} < \mu_{02}, \mu_{30} < 0. \end{cases}$$

The easiest option for determining the angular position of the object of measurement is based on the measured coordinates of two reference points of this object by the formula[36, 37]:

$$\alpha = arctg\frac{y_l - y_j}{x_l - x_j}.$$

The geometric parameters determined in such way are the initial data for the calculation of the parameters of motion and other mechanical quantities that characterize the objects of measurement. The parameters of the motion of objects of measurement can be determined on the basis of time sequence of video images, which characterizes the spatial position of objects of measurements at moments of time. For example, linear and angular displacements of contour points and center of masses of objects of measurements, linear and angular velocities of these points. If a priori information is known about the three dimensional geometric shape and the spatial arrangement of the object of measurement, then the volume and area of the

[35] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[36] Анисимов Б.В., Курганов В.Д., Злобин В.К. Распознавание и цифровая обработка изображений: учеб. пособие для вузов. Москва, 1983. 295 с.

[37] Введение в контурный анализ; приложения к обработке изображений и сигналов / Я.А. Фурман, А.В. Кревецкий, А.К. Передреев и др.; под ред. Я.А. Фурмана. Москва, 2003. 592 с.

intersection of this object can be estimated on the basis of the video image. If a priori information is known about the volume density of the object of measurement or its density, as a flat figure, then we can determine the mass of this object. If the mass of the object of measurements is known, then external forces can be estimated on the basis of measurements of its parameters of motion as well asthe moments that influence this object. Based on the calculated area of intersection of the object of measurement and external force that is perpendicular to the plane, the mechanical stresses in this object can be determined. The mechanical deformations of this object can be determined on the basis of displacements of the objects of the measurements measured for the time sequence of the video images.

The obtained results of measurements of mechanical quantities can then be used in automated control systems for the quality management of industrial products as well as in controlling the operation of equipment and the progress of technological processes, other production tasks.

2. Principles of constructing of measuring instruments of geometric object parameters based on their video images

The measuring system for determining geometric parameters of objects is based on the following principles:

1. Use of existing technical means for forming video images of objects of measurement that are capable to provide high resolution and performance[38, 39, 40]. Therefore, the development of new technical means for the measuring system is inexpedient.

2. Application of computerized processing of video images. The purpose of computerized processing is algorithmic compensation of video image errors as well as measurement errors of geometric parameters of objects. Thus, a significant increase in the accuracy of measurements is provided. The use of modern methods

[38] Шапиро Л., Стокман Дж. Компьютерное зрение. Москва, 2006. 752 с.
[39] Шлихт Г.Ю. Цифровая обработка цветных изображений. Москва, 1997. 336 с.
[40] Шарыгин М.Е. Сканеры и цифровые камеры. Санкт-Петербург, 2000. 384 с.

for the accumulation, analysis and visualization of video images and the results of measuring geometric parameters also expands the functional capabilities of the measuring system.

3. Development and use in the measuring system of new methods of computerized processing of video images (methods of filtration and restoration of video images, methods of searching and selection of objects of measurement, methods of approximation of contours and trajectories of motion of objects of measurement). These methods should take into account the high requirements for the accuracy and speed of measurement of geometric parameters and parameters of motion of objects of measurement.

4. Development and use of video conversion and compression methods in the measuring system. The purpose of these methods is to increase the accuracy and compactness of the measurement information about the geometric parameters when it is accumulated and stored, increasing the speed of the measuring system.

5. Use of time sequences of video images to identify parameters of movement of objects of measurement. In order to identify traffic parameters, it is necessary to further develop methods for computerized processing of video images in real time based on the theory of identification of technical systems. The identification results are used to compensate the dynamic errors of measuring the geometric parameters of objects moving in the measurement process.

6. Optimization of the parameters of the measuring system in accordance with the current characteristics of the objects of measurement and the conditions for measuring geometric parameters. Including – optimization of parameters of video images, parameters of technical means of the measuring channel and parameters of computerized processing of video images. It should be borne in mind that increasing the accuracy and speed of the measuring system are tasks that put different requirements to these parameters. Therefore, you need to use optimization methods. The result of solving optimization problems is to increase the accuracy of the measuring system at a given speed or increase the speed at a given accuracy.

7. Use of modern technologies of visualization of objects of measurement and processing of measuring information on the basis of the theory of artificial neural networks. These networks adapt and optimally adjust the parameters of the measuring system in accordance with the working conditions of measuring geometric parameters, characterized by the influence of adverse and non-stationary factors. The result of the application of artificial neural networks is the compensation of additional error of measurement of geometric parameters and parameters of motion of objects of measurement under the indicated conditions. If a neuroprocessor is used, then a significant increase in speed is also provided.

On the basis of the developed principles of construction a new measuring system for measuring geometric parameters of objects has been created (Fig. 1).

In fig. 1 marked: OM – object of measurements; PE – production equipment; T OM – test object of measurements for calibration of the measuring channel; DFVI – a device for the formation of video images (digital video camera); OS – optical system of DFVI; LSC – “light-signal” converter; VIA – video image amplifier; ADC – analog-to-digital converter; RD1 ... RD3 – remembering devices for video images; BEVI – block of encoding of video images; CU – control unit of DFVI; VTVI – a device for transferring video images to a computer; NP – neuroprocessor in the computer; z^{-1} – block of delay; $c_1 ... c_s, b_0 ... b_r$ – weighted coefficients of the artificial neural network, which are adjusted according to the current measurement conditions; BAF – a block of the activation function of the neural network; P – central processor; VD – visualization device for video images and results of measuring geometric parameters of objects.

In the measuring system, the computer is used as a video image processing device, which additionally includes a neuroprocessor. The neuroprocessor contains the basic elements of artificial neural networks, which are connected in a certain sequence and are used for the recovery of video images with random and dynamic errors in measurement information about geometric parameters, for searching and selection of objects of measurements and their structural elements on video images. Typically, these computerized processing operations are based on a priori information about the video image and their errors.

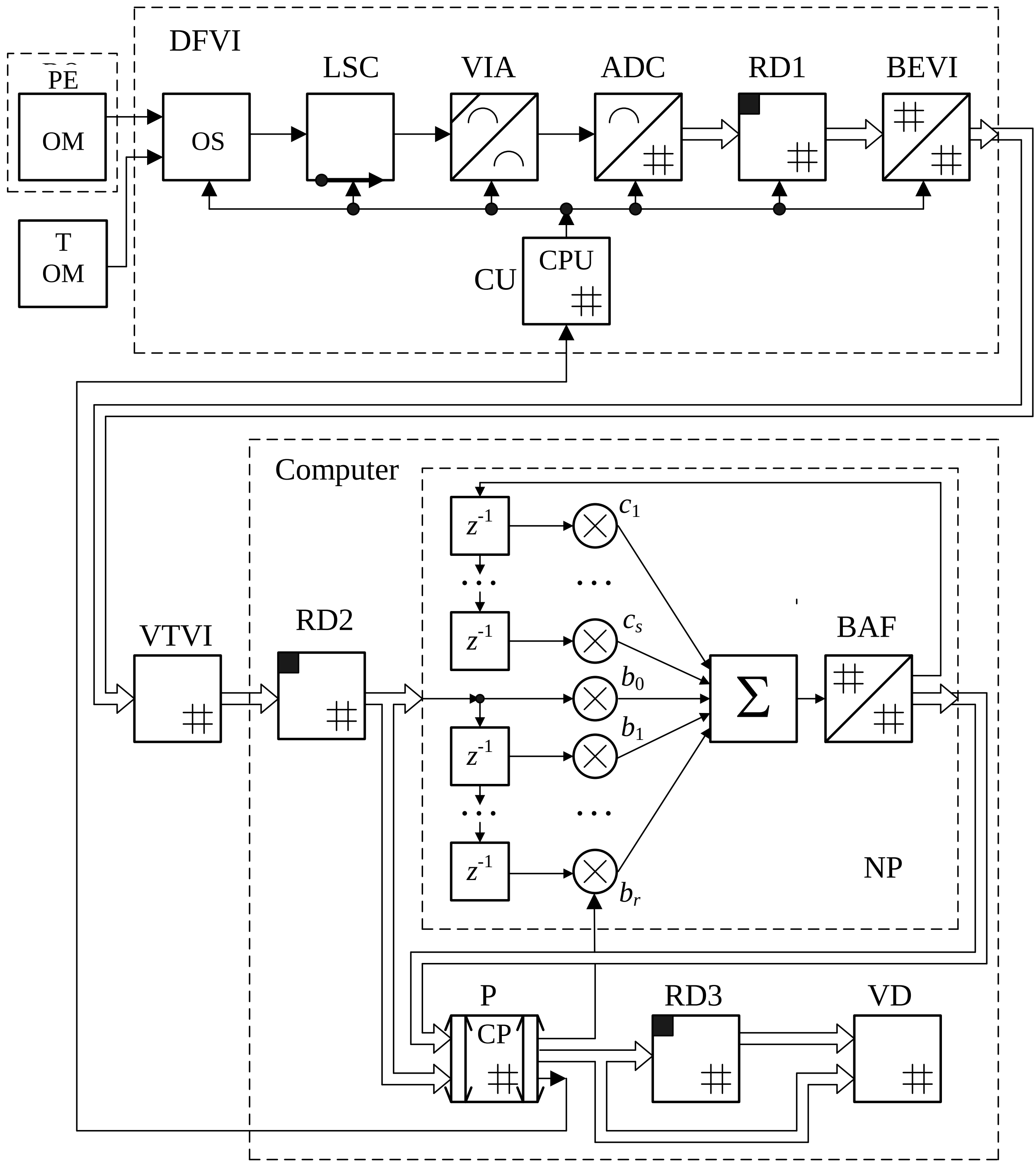

Fig. 1. Measuring system for measuring geometric parameters of objects on the basis of computerized processing of video images

This information corresponds to the normal measurement conditions and the averaged value of the video image and digital video camera. In the working conditions of the measurements, these parameters may deviate from the values used in the calculations. As a result, an additional error of measurement of geometric parameters and parameters of motion of objects is compensated. Thanks to the adaptive properties of the artificial neural network, the parameters of video image processing algorithms can be adjusted in accordance with the current measurement conditions and properties of the measuring objects. As a result, additional error is compensated and the accuracy of measurement of geometric parameters of objects is significantly increased. With the use of a neuroprocessor that performs high-speed parallel processing of digital data of video image, the speed of the measuring system is also substantially increased.

In order to measure the geometric parameters of objects, computerized processing of their video images is used. In this optical-electronic methods, a video image of measuring objects is formed. This is accomplished by scanning a two-dimensional image of objects of measurement, created by the optical system on the surface of the matrix converter “light-signal”. For computerized processing of formed video images, video filtration and restoration methods, methods of searching for and selecting the contours of objects of measurement and the set of points belonging to these objects are used. As a result, the coordinates of the points belonging to these objects are measured.

The results of the coordinates of the points are used to calculate the geometric parameters (linear dimensions and angles) along the external contour of the objects of measurement, as well as the geometric parameters of the structural elements of the surface of these objects (length and width, area, angle of orientation of the main axis of inertia, morphometric characteristics, coefficients of geometric form). The parameters of motion of products and other mechanical quantities are determined by computerized processing of time sequences of video images with measured geometric parameters.

During the calibration of the measuring channel of the measuring system, test objects of measurements with known linear dimensions are used to determine the scale factors $k_{мx}$, $k_{мy}$ in the measurement equations (2); test objects of measurements with known surface characteristics and procedures for adaptation and training of artificial neural networks, which allow to compensate the influence of non-stationary and unfavorable factors on the measuring system in the conditions of industrial enterprises.

3. Ways to improve the accuracy and speed of the measuring system to determine the geometric parameters of objects

Digital video output on the digital video camera contains the following errors:

– errors caused by the discrete nature of digital video images[41];

– random errors caused by noise of the optical system, thermal and fractional noise in the semiconductor converter “light-signal” and in electronic circuits[42, 43];

– dynamic errors due to the limited capabilities of a digital video camera for the formation of video images, whose amplitude is rapidly changing in space and time[44, 45, 46];

– errors due to quantization of the amplitude of the video signal on digital video images[47, 48, 49];

– geometric errors due to the distortion of the optical system[50, 51, 52], the difference between the geometric shape of the objects of measurement from the plane, the non-perpendicularity of the controlled surface of the products and the optical axis of the digital video camera;

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[41] Цифровое преобразование изображений: учеб. пособие для вузов / Р.Е. Быков, Р. Фрайер, К.В. Иванов, А.А. Манцветов; под ред. Р.Е. Быкова. Москва, 2003. 228 с.

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– errors caused by encoding and converting digital data of video images in order to reduce their volume when accumulated and stored[53, 54, 55, 56].

The listed video errors affect both the amplitude of the video signal as well as the coordinates and geometric shape of the contours of objects. But when measuring geometric parameters, it is first necessary to estimate the errors of determining the coordinates of the contour points of the objects of measurement. To do this, you need to gather the calculated marks of all errors to one indicator, which characterizes the accuracy of measuring the coordinates of points and other geometric parameters on this basis.

Therefore, a method for estimating distortions of digital video images with measurement information about geometric parameters of objects of measurement has been developed. This technique consists in the following sequence of actions:

1. Estimation of the mean square error value of the reproduction of the amplitude of the digital video image is calculated:

$$\sigma_{\Delta f} = \sqrt{\frac{1}{MN}\sum_{n,m}\left(f_{\mathrm{F}}(n,m) - f_0(n,m)\right)^2}, \tag{3}$$

where $f_0(n,m)$ – a digital video image containing discrete countdowns of a two-dimensional function $f_0(x,y)$.

2. A search for the amplitudes of the video signal corresponding to the contours of the objects of measurement, by analyzing the changes of this amplitude in the lines or columns of the digital video image is performed.

3. Average height value h_{C} variations of the amplitude of the video signal corresponding to the contours of the objects of measurement, and the mean value of the length l_{C} projections of these variations to a given coordinate axis in the plane of the video image by linear approximation of these variations are determined. For the digital video camera, the parameters of the differences can be determined by

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[53] Претт У. Цифровая обработка изображений. Москва, 1982. 792 с.
[54] Гонсалес Р., Вудс Р. Цифровая обработка изображений. Москва, 2005. 1072 с.
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analyzing the test images containing the boundary curve (the boundary between the object of measurement and the background).

4. Calculation of the mean square value $\sigma_{\Delta x}$ of error of determining the coordinates of contour points of measurement objects are made:

$$\sigma_{\Delta x} = \sigma_{\Delta f} \cdot l_C / h_C. \quad (4)$$

If the length of the difference is expressed in d.p., then to receive $\sigma_{\Delta x}$ in units of length (meters or millimeters) the result of calculations is additionally multiplied by k_{mx} (according to the formulas (2)).

Formula (1.6) can be used for numerical simulation of a measuring system with a priori known properties of test objects. In this case, a digital video image $f_F(n,m)$ is received at output of the digital video camera, and the original video image $f_0(n,m)$ of test object of measurement is known. For experimental studies of real objects, the original digital video image $f_0(n,m)$ is unknown. Then, the estimation of the amplitude error is calculated on the basis of the signal-to-noise ratio, which is calculated in the television equipment by the formula[57, 58]:

$$\sigma_{\Delta f} = \frac{A_{max}}{10^{\psi_{s/n}/20}}, \quad (5)$$

where A_{max} – maximum value of the amplitude of digital video images (when encoding amplitude using 8-bit binary code $A_{max} = 255$ of discrete levels (d.l.)), $\psi_{s/n}$ – signal / noise ratio for digital cameras.

The results obtained by formulas (3) and (5) are used as an average evaluation of the quality of video images. Formula (4) is used to calculate the accuracy of measuring the coordinates of points and geometric parameters on this basis. This accuracy is expressed in units of length.

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[57] Птачек М. Цифровое телевидение. Теория и техника. Москва, 1990. 528 с.

[58] Зубарев Ю.Б., Глориозов Г.С. Передача изображений: учебник для вузов. Москва, 1982. 224 с.

The most significant error in determining the coordinates of the points is due to the discrete nature of digital video images[59, 60]. Its value is determined by the field of view of the optical system of a digital video camera and the total number of points on a digital video image. The error has a uniform distribution in the range $\pm\delta_x/2$ or $\pm 0{,}5$ d.p. with zero mean value.

The error determines the maximum possible accuracy of measuring the coordinates of one point of the digital video. This error can not be compensated by algorithmic methods for one-time measurement of the coordinates of one point. Therefore, in order to improve the accuracy of this coordinate measurement, it is necessary that the other digital video image errors on the output of the digital video camera are significantly less than the error.

To further improve the accuracy of determining the geometric parameters of objects, it is necessary to develop methods for algorithmic processing of coordinates of a plurality of adjacent points belonging to measurement objects within a single digital video or a time sequence of digital video images. The basis of these methods is the approximation of contours of objects of measurement and labels of a priori known form, which are applied to the surface of objects. An example of these procedures is the linear approximation of facets of industrial products made of natural stone of rectangular shape.

The most known method for such approximation is the least squares method. The application of this method requires the implementation of a number of conditions[61]. For example, the value of the linear function argument (coordinates x_j) must be known exactly. In the case of using digital video images, the results of coordinate measurement of contour points contain errors and this condition is not fulfilled. Therefore, it is necessary to develop methods for approximating the coordinates of contour points, which are sensitive to these errors. The basis of

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[59] Цифровое преобразование изображений: учеб. пособие для вузов / Р.Е. Быков, Р. Фрайер, К.В. Иванов, А.А. Манцветов; под ред. Р.Е. Быкова. Москва, 2003. 228 с.

[60] Шлихт Г.Ю. Цифровая обработка цветных изображений. Москва, 1997. 336 с.

[61] Грановский В.А., Сирая Т.Н. Методы обработки экспериментальных данных при измерениях. Ленинград, 1990. 288 с.

development are robust and confluent methods of constructing dependencies on experimental data[62, 63].

Non-stationary and unfavorable factors in the working conditions of measuring geometric parameters lead to the appearance of additional measurement errors. To compensate for these errors, additional adjustments and optimization of the parameters of the measuring system in the process of operation are required. Therefore, it is proposed to optimize the parameters of the measuring system to perform both at the development stage, and in the process of its operation in order to adapt to the impact of nonstationary and adverse factors. Such adaptation and optimization can be accomplished with the help of artificial neural networks as a tool for computerized processing of video images. An important feature of artificial neural networks is the presence of built-in training procedures, the results of which compensate for the additional error of measurement of geometric parameters.

Thus, the main ways to increase the accuracy of measuring geometric parameters of objects are as follows:

1. Algorithmic compensation in the computer of random, dynamic and geometric errors of video images.

2. Approximation of contours of objects of measurements. As a result, the errors caused by the discrete nature of digital video images are offset.

3. Identification of the parameters of motion of objects of measurement on the basis of methods, which are not sensitive to the errors of measurement of the current coordinates of these objects. Compensation on this basis of dynamic errors in the measurement of geometric parameters due to the movement of measurement objects in the measurement process.

4. Optimization of the parameters of the measuring system in order to reduce errors, including – due to the discrete nature of digital video images and their encoding.

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[62] Грановский В.А., Сирая Т.Н. Методы обработки экспериментальных данных при измерениях. Ленинград, 1990. 288 с.

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5. Use of artificial neural networks for computerized processing of video images in order to adapt and optimize the parameters of a measuring system in working conditions for measuring geometric parameters characterized by the presence of adverse and non-stationary factors. Improved accuracy by compensating for additional errors.

The main ways to increase the speed of measuring the geometric parameters of industrial products are as follows:

1. The use of the advantages of video images that simultaneously characterize the properties of objects of measurement at many points in space. This means that one video, formed by modern technical means in a short period of time, can replace the results of tens and hundreds of measurements carried out by existing measuring instruments over a significant period of time.

2. Use of artificial neural networks and neuroprocessors for computerized processing of video images and results of measuring geometric parameters. Neuroprocessors provide processing of digital video in parallel mode for performing high-speed computing.

3. Measurement of the geometric parameters of industrial products directly in the process of their movement relative to the measuring system, which is due to the technological process of manufacturing these products. Development for such measurements of algorithmic processing of video images that can be performed in real time and provide compensation for the dynamic error of measurement of geometric parameters due to movement of products.

4. Algorithmic processing of digital video images separately in rows and columns. This approach provides a significant reduction in the number of computing operations.

5. Optimization of digital video parameters and parameters of the measuring channel.

Improvement of the technical characteristics of the desymbalating system should be carried out by increasing its accuracy with given performance indicators or increasing the speed at given accuracy indicators in accordance with the requirements of specific application problems solved in industrial enterprises.

CONCLUSIONS

The measuring system has an increased accuracy (2.5 ... 3.0 times, an error of measurement of linear dimensions of 0.1 mm, angles of 26 angular seconds for industrial products with a maximum size of 1500x1200 mm) and performance (tens of times, the time of measurements for one product 3.0 s), expanded functionality of registration, analysis, storage and display of measurement information about geometric parameters in comparison with existing measuring instruments. These results are achieved on the basis of the proposed principles of constructing a measuring system and measures on algorithmic compensation of errors and increasing the speed of measurement of geometric parameters of objects in their video images.

SUMMARY

The results of research are aimed at solving the scientific and technical problem of increasing the accuracy and speed, expanding the functional capabilities of measuring instruments of mechanical quantities (including - the geometric parameters of objects of measurement) through the formation and computerized processing of their video images.

On the basis of video images geometric parameters and parameters of motion of objects of measurement, as well as other mechanical values depending on these parameters can be defined. The coordinates of the points belonging to the object of measurements are directly measured on a digital video image. Geometric parameters are determined by computerized processing of the results of the measurements of the coordinates of these points.

The basic principle of constructing the offered measuring instruments is the use of the methods of visualization of objects of measurement with the formation and computerized processing of their video images. Including - these are methods based on the theory of artificial neural networks. These methods allow to compensate for

the additional error in working conditions of measurement of geometric parameters at industrial enterprises. The purpose of computerized processing of video images is compensation of errors of measurement information that arose in the process of forming and transferring video images to a computer.

The limit of accuracy for the result of measuring the coordinates of one point of measurement objects is the error due to the discrete nature of the digital video image. This error is equal to half the distance between centers of adjacent points and determines the boundary accuracy of calculations of geometric parameters, parameters of motion and other mechanical quantities by computerized processing of the results of measuring coordinates. In order to further improve the accuracy of the determination of the specified values, it is necessary to use methods of computerized processing of coordinates of a plurality of points belonging to objects of measurement within the limits of one video or time sequence of these video images. The basis of such methods is the approximation of the contours and trajectories of the objects of measurement.

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Information about author:

Podchashinskiy Yu.,

Doctor of Science in Technology, Head of the Department

of Metrology and Information-measuring Equipment,

Zhytomyr State Technological University

103, Chudnivska str., Zhytomyr, 10005, Ukraine

Syvak Olena,

Candidate of Economic Sciences,

Assistant Professor

of the Department of Foreign Languages
Zhytomyr State Technological University
103, Chudnivska str., Zhytomyr, 10005, Ukraine