Application of the electrooptical method for the analysis of surface nanoroughness of raceways of instrument bearings

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Abstract. The control of the microrelief of surfaces of small-size details is a relevant objective for the mechanical engineering. We consider the issue of control by reference surface fragment with the radius of curvature comparable to the size of the fragment. We offer an optical method that uses the binary images of the target and the reference surfaces to control the nanoroughness of raceways of instrument bearings. A quasi-optimal correlation algorithm is used to compare two surface images. The value of the autocorrelation function allows to evaluate whether the roughness of the ring raceway of the instrument bearing corresponds to the norm. The results of the tests of the developed method showed its statistical stability. This allows us to use the method in serial production conditions. The results of nanoroughness analysis of surface with the roughness up to 0.02 microns after grinding with abrasive circles are provided.

1. Introduction
The surface quality of raceways of instrument bearings determines their service properties. The durability and reliability of the bearings is determined by the height, shape and location of nanoroughness on the raceways [1]. However, the existing nanoroughness control methods used in optics and microelectronics [2-8] cannot be used in serial production of surfaces with high curvature.

There exist the methods of rough surface parametrization [9] and the devices for the control of bore surface defects [10]. However, the parametrization of a bore surface requires the diffused lighting of nanoroughness, which is difficult to provide for the rings of instrument bearings. The device [10] is effective for the control of the surface of a bore with the diameter of at least 30 mm. So, it is impossible to control the bore surface of instrument bearings with an average diameter of less than 30 mm.

2. Description of methods
Machine vision methods based on noncontact digital image processing [16-19] are the most acceptable methods for the submicron roughness control [11-15]. Such control methods have the following disadvantages:
- the presence of microrelief shading zones with the size and shape depending on the spatial orientation of the light source [9, 20-22];
- the use of coherent light sources leads to the interference and diffraction of incident light rays and the rays reflected from the target surface [23-28].

Both of these circumstances distort the real picture of the target surface microroughness [9-12].

The manufacturing practice has shown: the biggest height of microroughness on the surface of raceways of instrument bearings is 0.02 μm (Rmax). We assumed that the smallest area of the base of a microroughness should not exceed 0.02 μm². For this reason, the resolution of the image of a microroughness should be at least 0.14 μm/pixel.

We offer an electrooptic system (IMS) [29, 30] which provides for the roughness control with nanometric resolution. The IMS includes an optical system, a video camera, a computer, and a custom algorithm for the processing of the target surface image [31]. Fig. 1 shows the structure of the information and measurement system.

![Image](image.png)

**Figure 1.** The structure of IMS for the evaluation of microrelief parameters.

The IMS consists of a target surface fragment (TSF), a reference light source (RLS), a video camera (VC), and a digital signal processing unit (DSPU). RLS and VC are the electrooptic measuring transducer (MT). RLS and TSF form the channel of primary optical relief conversion system. A transformed TSF is fed to the input of electrooptic MT. The transformation of the TSF consists in splitting the fragment of the target surface into r types of elementary non-intersecting surface elements with different nanorelief. A certain parameter is assigned to each element. The weighted average parameter of all surface elements was calculated to parametrize the entire TSF:

$$P_{\mu} = \sum_{i=1}^{r} \alpha_{pi} \cdot P_{\mu i},$$

where $P_{\mu i}$ is the $i^{th}$ component of the input value of the transformed nanorelief parameter, e.g., $Ra$; $\alpha_{pi}$ is the weighting factor corresponding to the share of TSF elements with nanorelief of the $i^{th}$ standard level (with the total number of standard levels estimated at $r$). The set of values $\{i = 1, \ldots, r \}$ is determined by the particular TSF machining.

The RLS output is the luminous power of the reference light $F_r$ reflected from each $i^{th}$ TSF element. Thus, each $i^{th}$ surface element forms the $i^{th}$ output of the primary optical relief conversion system (the luminous power of the reflected light flux $F_{o(i)}$), which is later transformed into the electric signal $U_{ei}$ with a CCD matrix.

We presented the nominal transformation function of the $i^{th}$ component of the input value $P_{\mu}$, corresponding to the $i^{th}$ subset of equally machined TSF elements in the following way:

$$U_{ei} = K_{fe} \cdot F_{o(i)} = (K_{fe} \cdot F_{nr}) \cdot (F_{o(i)/F_{nr}}) = (K_{fe} \cdot F_{nr}) \cdot Y_{o(i)} =$$

$$= (K_{fe} \cdot F_{nr}) \cdot f(P_{\mu}) \leq P_{\mu_{min}} \leq P_{\mu} \leq P_{\mu_{max}}$$

where $K_{fe}$ is the coefficient of physical transformation of power of light flux $F_{o(i)}$ into the electric signal $U_{ei}$ (the value of $K_{fe}$ is constant for the considered ranges of $P_{\mu}$ and $F_{nr}$); $F_{nr}$ is the nominal value of $F_r$; $F_{o(i)}$ is the nominal value of the luminous power of the reflected light flux $F_{o(i)}$ from any element of the $i^{th}$ subset of TSF elements; $P_{\mu_{min}}$ and $P_{\mu_{max}}$ are the boundaries of the used range of $P_{\mu}$; $f(P_{\mu})$ is the functional dependence of the nominal values of the standardized output of optical relief conversion system $Y_{o(i)}$ on the $i^{th}$ component of the measured value $P_{\mu}$. In other words, $Y_{o(i)}$ characterizes the reflective power of the $i^{th}$ component of TSF on exposure to the light flux with the power $F_{nr}$.

We approximated the function $f(P_{\mu})$ with the $m^{th}$ degree polynomial:

$$f_{ap} (P_{\mu}) = \sum_{p=0}^{m} a_p \cdot P_{\mu}^p,$$

$$= \sum_{p=0}^{m} a_p \cdot P_{\mu}^p.$$
where $a_p$ is the polynomial approximation coefficient.

In the paper [31] we considered a monochrome raster image of a rough surface fragment. The number of brightness gradations per image pixel was 256.

The nominal luminous power of the reference light amounted to $F_{nr}=600 \times 10^{-3}$ lm, the powers $F_{r \min}, F_{r \max}$ amounted to $200 \times 10^{-3}$ lm and $1000 \times 10^{-3}$ lm. The said range of $F_r$ corresponds to the factory conditions.

We believe that the reasons for changing the luminous power are as follows:
- variations in supply voltage of light sources;
- changes in the atmospheric transparency at the workplace;
- stray lighting of the target surface from the external light sources, etc.

In the paper [31] we have determined that the interference effects have a multiplicative nature. Then we denote the deviation of the reference luminous flux from its nominal values by $\Delta F: \Delta F = F_r - F_{nr}$, and we denote by $f_{inf} (\Delta F)$ the multiplicative function of the influence of deviations like $\Delta F$ on the results of measuring transformations $Y_{oi}$.

We considered the function of $F_{oi}$ transformation into the electric signal $U_{ei} (i = 1, \ldots, r)$ in the following way:

$$
U_{ei} = (K_{fe} * F_{nr}) * (F_{oi}/F_{nr}) = (K_{fe} * F_{nr}) * Y_{oi} = 
(K_{fe} * F_{nr}) * f_{inf} (\Delta F) * f (P_{\mu})
$$

were approximated the function of interference effects with the $n^{th}$ degree polynomial with the accuracy sufficient for the manufacturing practice:

$$
 f_{inf} (\Delta F) = 1 + \sum_{k=1}^{n} b_k * (\Delta F)^k,
$$

where $b_k$ is the coefficient at the power of $(\Delta F)^k$ defined according to the experimental data. We shall note that this function takes the value of 1 at the nominal value of the reference light $F_{nr}$.

The multiplicative character of the function $f_{inf} (\Delta F)$ determined the choice of ratiometric method of compensating the error of roughness control [32]. The use of ratiometrics involves the use of an additional light source. This is unacceptable when controlling the surface roughness of raceways of instrument bearings.

We offer a method of correction of the error caused by the instability of the reference luminous flux. In this case, the optical correction scheme uses one light source.

The method proposed by us is based on the observing a one-to-one correspondence between the set of quantities $(Y_{ei} (X_{\mu}), i = 1, \ldots, r)$, and two functionals $G_x (Y_{ei} (X_{\mu}), i = 1, \ldots, r)$. Here $x = 1, 2$ is a set of values.

In our opinion, the effect of the factors distorting the measurement results (influence function, interference) on the measured values has a multiplicative nature. For this reason, we considered the products of the type $q_x (X_{\mu}) = f_{inf} (\eta_x)$, where $q_x (X_{\mu})$ is the functional relationship that corresponds to the inequation $q_x (X_{\mu}) = q_0 * q_2 (X_{\mu})$; $q_0 = \text{const}$.

In the quotient

$$
G_1 (Y_{ei} (X_{\mu}), i = 1, \ldots, r)/G_2 (Y_{ei} (X_{\mu}), i = 1, \ldots, r)
$$

similar multiplicative components $f_{inf} (\eta_x)$ in numerator and denominator are canceled. Thus, the realization of the quotient (1) does not lead to the hardware growth in IMS, as the same set of values $Y_{ei}$ will be used in the formation of each functional $G_x (x = 1, 2)$.

We applied the theory of optimal linear filtering of signals of the known format to implement the proposed method of error correction [33]. Besides, we used the methods of digital image processing [34, 35]. The method is based on the detection of the known nanoroughness of the target surface. For this purpose we compared the image of the target surface with the images of the reference surface with the nanoroughness parameters defined in accordance with the national standard GOST 2789-73 and the international standard DIN EN ISO 4287-2010. The result of the comparison is the probability that the target and the reference surfaces match. The choice of the threshold for the probability that the images match determines the permissible level of interference and noise in the target image (influence function $f_{inf} (\Delta F)$). However, the threshold probability does not define the nature of the difference
between the two images. In such cases, correlation analysis is used to identify the linear dependence of the characteristics of the target and the reference roughness. We believe that when the dimensions of the target surface image are small, it is advisable to use the Spearman correlation [36]. We used a high-resolution video camera in IMS. For this reason, the raster image of the target surface fragment had a large number of lines and columns. This allowed us to use the Kendall correlation coefficient [34] as a criterion for comparing the surface with the unknown type of nanomicroroughness and the reference surface with nanoroughness [31]:

\[
 r_{xy}(k_1, k_2) = \frac{\Sigma_{n_1=0}^{N_1-1} \Sigma_{n_2=0}^{N_2-1} [u(n_1, n_2) - m_u] \cdot [x(n_1-k_1, n_2-k_2) - m_x] \cdot f_{inf}(\Delta F)}{\sigma_x \cdot f_{inf}(\Delta F) \cdot \sigma_y \cdot f_{inf}(\Delta F)}
\]  

(2)

A monochrome image of the target surface is stored in DSPU memory. Here \( u(n_1, n_2) \) is the image of the reference surface fragment embedded in the reference surface (in the search zone \( x(n_1, n_2) \)); \( \sigma_1 \) and \( \sigma_2 \) are the mean square deviations of the values \( u(n_1, n_2) \) and \( x(n_1, n_2) \) from their mathematical expectations \( m_u \) and \( m_x \).

\[
\sigma_1 = [\Sigma_{n_1=0}^{N_1-1} \Sigma_{n_2=0}^{N_2-1} (u(n_1, n_2) - m_u)^2 / M]^{1/2} \quad \text{and} \quad \sigma_2 = [\Sigma_{n_1=0}^{N_1-1} \Sigma_{n_2=0}^{N_2-1} (x(n_1, n_2) - m_x)^2 / M]^{1/2}.
\]

Here \( M = N_1 \times N_2 - 1 \) is the number of sampling points in the compared images.

As can be seen from the above expression for \( r_{xy}(k_1, k_2) \), its structure corresponds to the structure of the expression (1). And the influence function \( f_{inf}(\Delta F) \) present in the numerator and denominator is canceled. Thus, the autocorrelation function used can be considered a particular case of the ratio (1), and we can claim that it has the desired compensation property without the need to involve the additional equipment.

To calculate the bivariate autocorrelation function according to the formula (2) for the image with the dimension \( K_1 \times K_2 \) pixels [29-31], we selected a strip with the width of \( N_2 \) pixels from the first line. In the middle of this strip we defined a comparator with the dimension of \( N_1 \times N_2 \) pixels (window), which was saved in DSPU. Then we moved the comparator window from the 1st column to the position where the last column of the window coincided with that of the strip. The movement was performed with the step of 1 pixel. Upon each alignment of the comparator \( u(n_1, n_2) \) and the actual fragment of the grayscale image \( x(n_1, n_2) \), a correlation coefficient was calculated according to the formula (2).

The fragments compared \( x(n_1, n_2) \) and \( u(n_1, n_2) \) belong to the same surface image. For this reason, we considered that \( r_{xy}(k_1, k_2) \) is the correlation coefficient. The window with the dimension of \( N_1 \times N_2 \) performed a scanning motion along all the strips of the image. The shift from line to line had the step of 1 pixel. A new comparator was defined in the center of each strip (with the dimension of \( N_1 \times N_2 \)). The values \( r_{xy}(k_1, k_2) \) determined were saved in DSPU. As a result, a matrix of autocorrelation coefficients was formed with the dimension \( M_1 \times M_2 \). The paper [31] proved the following: the values of autocorrelation function \( r_{xy}(k_1, k_2) \) for nanoroughness of various surfaces are substantially different from each other (the comparator window changed from 16×16 to 8×8 pixels). However, the excess of \( \Delta U_{AV} \) between the studied nanorelief parameters remained almost unchanged.

The roughness parameter of the image surface was taken as a standard roughness parameter \( Ra_n \), which is different from the height of the surface contour roughness. Thus, based on calculating \( U_{AV} \) for the target surface, its size can be defined by making an analytical dependence \( Ra_n = f(U_{AV}) \) for comparators with the known nanorelief.

The disadvantage of the proposed method of nanoroughness control based on the calculation of the correlation coefficient takes a lot of computer time. So, for example, when using a personal computer with an Intel(R) Core(TM)2CPU 4300@1.80GHz processor, the time spent on this calculation is 160000 ms for a comparator with the dimension of 64×64 pixels. This excludes the use of this method for the operational control of the surface nanoroughness under the production conditions.

To eliminate this disadvantage, we used quasi-optimal algorithms to calculate the criterial functions [37–45] which include the two-dimensional autocorrelation function discussed above. In the works cited, it is noted that the existing quasi-optimal correlation algorithms had been developed heuristically. This complicates the optimal choice of the algorithm. In our opinion, the algorithm for solving the problem should include the following steps:
1) selection of the type of image preprocessing;
2) determination of the criterial function;
3) determination of the method for calculating the extremum of the criterial function.
In this article we will not consider the third stage. This will be the subject of our future research.
The list of the requirements for the criterial functions is considered in [39, 40].
The analysis performed in [40, 41] allowed us to distinguish five groups of criterial functions with
similar properties: correlation, spectral, difference, paired and rank.
The proposed method of applying a quasi-optimal correlation algorithm was used to determine the
nanoroughness of a raceway of the inner ring of instrument bearing No. 2000083 made of steel ShKh-
15 HRC 62-65.
The scheme of grinding the track surface is shown in Fig. 3
The grinding mode for the raceway of the inner ring of instrument bearing on the grinding machine
Bryant 1-M was as follows:
spindle rotational speed – $n_w = 1750 \ldots 1850$ rpm;
efficiency output – $\eta = 0.8$;
grinding wheel size – $D_w = 355$ mm, $H_w = 16$ mm;
abrasive disk used for rough finishing – 24AM40CT1K;
wheel dressing: cross feed $S_{\text{cross}} = 0.015$ mm/motor motion, length feed $S_{\text{length}} = 0.02$ rpm, feed per
minute $S_{\text{min}} = S_{\text{length}} \times n_o = 0.02 \times 1850 = 37$ mm/min, dresser diamond $\alpha = 90^\circ$, dressing time $\tau = 15$ sec.
The studied bearing ring has the outer circle radius of 2.5 mm and the raceway cross-section radius
of 0.3 mm. The area of the target surface had the size of 1.2-1 mm, which corresponded to the image
dimension of 720x576 pixels.
When the direction of the illuminating light flux is perpendicular to the direction of the raceway in
the focal plane of the optical system, we observed a very strong bright spot at small angles of
incidence of the light flux ($\alpha = 0^\circ \ldots 15^\circ$) or the appearance of a shadow from the ring edge at large
angles of incidence ($\alpha > 15^\circ$). We explain these phenomena by the curvature of the test surface. We
have found that in order to reduce these phenomena, the illuminating light flux should be directed
along the raceway and at a large angle $\alpha = 700$. The images of the surfaces of reference samples
with a dimension of 720x576 pixels shown in Fig. 2 were obtained with such an orientation of the
light flux.

![Figure 2](image_url)

**Figure 2.** Images of the reference surfaces made of steel ShKh – 15 with the image dimension of
720x576 pixels.

The rough surface parameters of the roughness comparators were determined using a SJ-201P
profilograph-profilometer.
We are not aware of the choice methodology [39, 40] for the type of pre-processing of the
roughness image and the type of the criterial function. For this reason, we selected the quasi-optimal
correlation algorithms on the basis of the experimental data.
Roughness control under the mass production conditions consists in determining whether the
surface fits the standard or not. Intermediate results (the need for various improvements) are not
relevant. In this regard, we believe that binary images should be used to control the nanoroughness. In
this case, paired criterial functions are used with the number of quantization levels equal to two.
There exist a lot of paired criterial functions [41, 42]. In this regard, there are ample opportunities
to create correlation-extreme algorithms. We have chosen an algorithm developed using the paired
criterial function in the following form:
\[
R(\Delta) = \frac{1}{N} \sum_{i=0}^{n-1} F_i(\Delta),
\]

where \( N \) is the number of elements compared between the comparator and the target image.

The initial grayscale image was binarized as follows:

- the original image of the target surface was divided into separate square fragments (windows), and the average level of video signal brightness \( B_T(x,y) \) was calculated for each window. This average level was the binary transformation threshold for the brightness of pixels in this window [45]. In the selected window, each pixel was converted;
- the movement of the window on the converted image is carried out with the step determined by the window size. As a result of the comparison of each element of the array \( B_i(x,y) \) with the threshold value \( B_A(x,y) \), a new value was assigned to it according to the rule:
  
  \[
  \text{if } B_i(x,y) \geq B_A(x,y) \Rightarrow B_i(x,y) = 0\text{FFH} \\
  \text{if } B_i(x,y) < B_A(x,y) \Rightarrow B_i(x,y) = 0\text{FH}.
  \]

Fig. 3 shows the binary images of nanoroughness comparators obtained using an adaptive binary transformation window with the dimension of 8 × 8 pixels.

![Binary images of nanoroughness comparators](image)

**Figure 3.** The binary images of nanoroughness comparators.

Earlier we have described the method of the comparator determination and the procedure of its scanning by the actual binary image to obtain a matrix of autocorrelation coefficients.

When using a quasi-optimal correlation algorithm, we counted the number of pixels that matched \( S_{xy} \) in the actual fragment of the binary image \( B_A \) and in the comparator \( B_C \). We calculated the ratio between the number of matched pixels and the total number of pixels in the image. The normalized sum thus obtained meets all the requirements of the stochastic connection provided in [40], in particular, \( 0 \leq r_{xy}(k_1,k_2) \leq 1 \). This allowed us to consider the normalized sum of the matched pixels as the value of the correlation coefficient \( r_{xy}(k_1,k_2) \). This method compensates for errors and noises resulting from the effect of the influence function \( f_{\text{inf}}(\Delta F,\Delta \alpha) \). This is due to the fact that at the point of coincidence of the values of the comparator pixels \( B_C \) and the pixels of the selected fragment of the actual binary image \( B_A \) it will be multiplied by zero, that is,

\[
\Delta B = B_A \times f_{\text{inf}}(\Delta F,\Delta \alpha) - B_C \times f_{\text{inf}}(\Delta F,\Delta \alpha) = f_{\text{inf}}(\Delta F,\Delta \alpha) \times (B_A - B_C) = f_{\text{inf}}(\Delta F,\Delta \alpha) \times 0 \text{ at } B_A = B_C.
\]

In addition, only at this point the above sum \( S_{xy} = S_{xy} + 1 \), that is, the measure of correlation of the comparator and the actual image fragment in accordance with the algorithm of paired criterial functions, grows.

For the nanorelief of the surfaces analyzed using IMS, we studied the influence of the surface nanoroughness of the comparators on the average amplitude of the variable component of the autocorrelation function \( R_{a,v} = f(U_{AV}) \). The results of the studies are shown in the table 1.

### Table 1. Dependence of the average amplitude of the autocorrelation function variation \( U_{AV} \) on the surface roughness at the surface image format of 720x576 pixels.

| Surface nanoroughness of the comparators | \( Ra_v =0.084 \mu m \) | \( Ra_v =0.048 \mu m \) | \( Ra_v =0.025 \mu m \) |
|------------------------------------------|------------------------|------------------------|------------------------|
| \( U_{AV} = 12.2 \)                     | \( \sigma = 1.3 \)     | \( U_{AV} = 9.9 \)     | \( \sigma = 0.8 \)     |
| \( \sigma = 7.86 \)                     | \( \sigma = 0.1 \)     | \( \sigma = 0.8 \)     | \( \sigma = 0.1 \)     |
For each comparator, 30 images were processed from different parts of the surface analyzed, that is, \( n = 30 \) and the standard deviation of the evaluation was determined by the formula [46]:

\[
\sigma_t = \frac{\sigma}{\sqrt{n}}
\]

In this case, the format of the comparator and the dimension of the binary conversion window for the studies performed was 8x8 pixels.

Therefore, if we set the recognition probability of the analyzed surface nanoroughness to \( P = 0.99 \) and \( t_\beta = 2.576 \), for the surface comparators with \( Ra_n = 0.084 \mu m \) we get \( \sigma_t = 0.24 \mu m \), for the surface comparators with \( Ra_n = 0.048 \mu m \) we get \( \sigma_t = 0.15 \mu m \), and for the surface comparators with \( Ra_n = 0.025 \mu m \) we get \( \sigma_t = 0.018 \mu m \). Using the expression for the confidence interval [24]

\[
I_\beta = (U_{AV} - t_\beta \times \sigma_t; U_{AV} + t_\beta \times \sigma_t),
\]

we get the following confidence intervals:

\[
Ra_n = 0.084 \mu m - I_\beta = 0.6 RU, \quad 11.6 RU \leq U_{AV} \leq 12.8 RU;
Ra_n = 0.048 \mu m - I_\beta = 0.4 RU, \quad 9.5 RU \leq U_{AV} \leq 10.3 RU;
Ra_n = 0.025 \mu m - I_\beta = 0.05 RU, \quad 7.81 RU \leq U_{AV} \leq 7.91 RU.
\]

As can be seen from the above data, the confidence intervals for \( U_{AV} \) increase with the growth of nanoroughness, but do not overlap, and the relationship \( I_\beta = f(U_{CP}) \) is non-linear. Using the least squares method, an analytical expression was obtained for this confidence interval in the following format:

\[
I_\beta = (0.09 \times U_{AV}^3 - 4.2 \times U_{AV}^2 + 68.5 \times U_{AV} - 314.9) \times 10^{-2}RU.
\]  

(3)

The autocorrelation surface and the graph of the autocorrelation function for nanoroughness are shown in Fig. 4. The data presented show a more homogeneous nature of the autocorrelation surface. Based on the graph of the correlation coefficient, the average amplitude of the variable component of the autocorrelation function for this case was \( U_{AV} = 8.24 RU \).

![Figure 4. The image of the autocorrelation surface and the graph of the autocorrelation function for the intact part of the instrument bearing raceway surface.](image)

Processing of the experimental data allowed us to get the regresional dependence \( Ra_n = f(U_{AV}) \) in the format:

\[
Ra_n = 0.0013 \times U_{AV} - 0.078 \mu m
\]

(4)

The use of the dependencies (3) and (4) gave the following results for the nanoroughness of the raceway surface: \( I_\beta = 0.15 RU, \quad Ra_{min} = 0.027 \mu m, \quad Ra_{max} = 0.031 \mu m \). The values obtained for \( Ra_n \) fully meet the specified technical conditions.

3. Conclusion

Thus, the use of the developed IMS and the surface microgeometry evaluation method based on the analysis of autocorrelation functions revealed the drawbacks of the grinding process of the inner ring runways of the instrument bearing No. 2000083 used in the production conditions. On the basis of the information received, the process of grinding the raceways in water coolant was developed and implemented, which allowed to reduce drastically the reject rate in this technological operation.

We plan to increase the capabilities of the proposed control method and the accuracy of roughness class assessment using a special structured-light system [21-22, 47-49] based on LED [50-53].
also advisable to use the proposed nanoroughness control method at the stage of studying the shape of the manufactured optical micro- and nanostructures [54-61], in particular, when designing the elements of computer optics [62-64] and the components of diffractive nanophotonics [65-70].

In conclusion of this work, we shall also note that we have patented the developed electrooptic complex and the method for determining the roughness of the target surface [71].

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