ABOUT ONE QUALITY MONITORING OF A SURFACE OF GEAR WHEELS

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Abstract: In the mass production of component in mechanical engineering, one of the most important criteria for the quality of component is surface quality. Usage of a defective component may lead to the failure of the entire assembly. Thus, for example, in the manufacture of a metal component, a defect leads to an increase in friction, heating of the assembled component and increased degradation. If the component is made from plastic, then the appearance of a surface defect can lead to further cleavage and failure of the assembly component operation. The origin of defects may be different, including tool deterioration in the manufacture of metal component, insufficient pressure in the injection-molding machine during the extrusion of plastics into molds, and many others. To control the shape of component, for example, gear teeth, identification methods based on various metrics were proposed in [9]. These methods consist of preliminary scanning of the control object, processing of the obtained image and selecting the necessary features by which the shape of the object is controlled. The proposed metrics allow us to determine deviations from the shape of controlled objects with the necessary accuracy, invariant to the group of affine distortions – the displacement, scaling and rotation of the component, but not projective distortions. The method proposed here also allows to take into account small projective distortions that inevitably arise with small positional deviations of the object. This approach allows real-time identification of the shape of the object and does not require the exact positioning of the object relative to the camera.

Key words: gear accuracy, measurement, metric, DTW, shape quality, image processing, pattern recognition.

1. INTRODUCTION

In mass production of parts, shape quality control is of particular importance. During the operation of automatic and semi-automatic lines for the production of detail, various surface defects are possible. These include inaccuracies in surface geometry, for example, deviation of tooth shape from involute or surface defects, such as chipping or pits [1-3]. The first case, as a rule, refers to metal detail obtained by metal processing, and the second is typical for both metal and plastic detail made by casting. Casting defects can be formed, for example, due to the ingress of gas bubbles, which causes chipping and pits. Surface deviations can be also due to oil leakage in hydraulic injection machines. In addition, surface geometry may be affected due to wear of the dies and punches when using the stamping technology. In all these cases, in mass production, the control process is hindered by the high rate of production of detail, which requires the use of non-contact control methods [4]. In addition, at a high rate of production of detail, the position of the detail on the conveyor can vary, that is, deviations such as shift and rotation are possible. In turn, a displacement in the position of the detail leads to small deviations in both size (scale) and small projective distortions. Thus, the quality control system for the shape of detail must be invariant to both affine and projective distortions (within reasonable limits). Well-known existing simple systems for controlling the shape of an object require fixing the detail in a certain position, and in more complex systems, remote control of the accuracy of the shape in most cases is based on expensive interferometers [5], the use of which is impossible with mass production of parts [6]. To solve this problem, it is possible to use video monitoring, in which the object is scanned with the resolution necessary for the specified accuracy [7]. Then, after preliminary processing of the image, the geometry of the surface of the detail is compared with the reference surface. The proposed methods ensure the invariance of measurements to changing the size of the object image (reduction/magnification of the image from the camera, shift of the object in the frame and its rotation relative to the direction of motion) as well as small projective distortions. The considered method ensures the independence of the measurement accuracy from the position of the object relative to the camera.

In the proposed technology, to ensure the necessary accuracy in the shape of parts, e.g., the shape of the gear tooth, we use image processing methods and algorithms for identifying the shape of objects based on the geometric correlation methodology [8-10] and dynamic time wrapping (DTW) [11], which allow identifying the shape of objects in real time with any predetermined accuracy. The first group of methods was described earlier in [10], however, the methods described in this paper are not invariant to projective distortions of the shape of the object.

In these methods, at the initial stage, an object image is scanned, pre-processed, and an object contour is obtained, as shown in Figure 1. Next, the contour is converted into a contour function as described in [8]. To control the accuracy of detail, the modified DTW method is used invariant to projective distortions [11], in which fragments of the sample are compared with fragments of the detail.

2. CONSTRUCTION OF CONTOUR FUNCTION

The proposed methodology for monitoring the quality of the shape of the object is based on photographing the object. Preliminary processing of the image consists in converting the image to black and white, filtering the noise, converting it to a binary image (two grade), and selecting the contour, as shown in Figure 1 [12, 13].

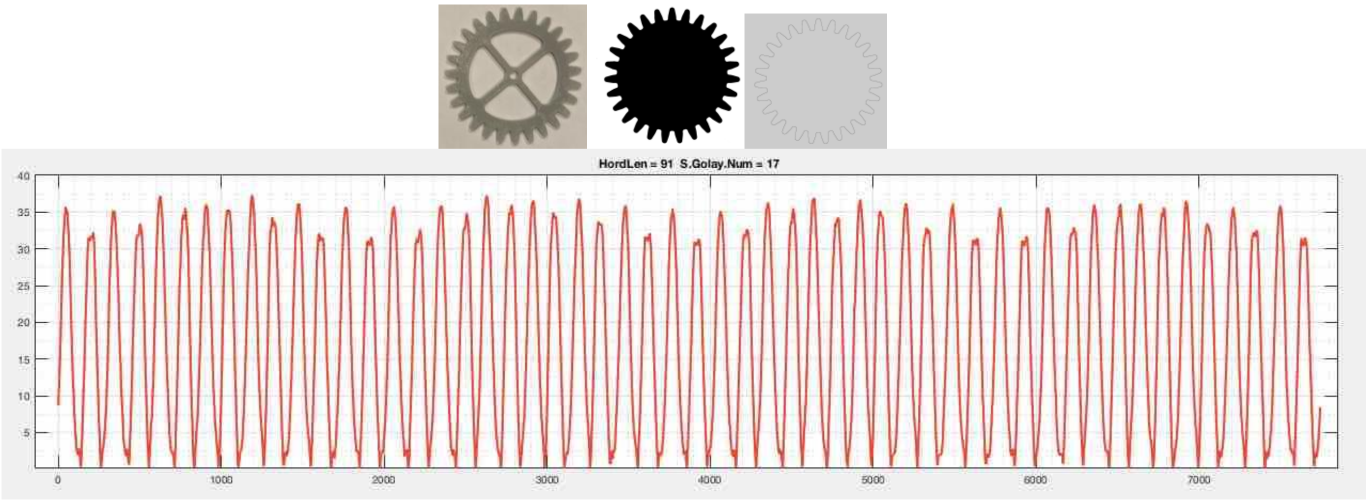

Fig. 1. Source Image (in top), Black-and-white image of the object, its selected contour, and the contour function, obtained by the ArchHeight method

Further, to identify the shape of the object, the resulting contour of the object, consisting of $n>1$ points $P_1, P_2, P_3, \ldots P_n$ of a closed parametrized planar curve $\Gamma(t) = (x(t), y(t)),\ 1 \le t \le n$ is used as an initial data set.

To construct the contour function of an object, the ArchHeight method is used, first published in 1992 [14] and then repeatedly modified [15]. The idea of this method is to calculate the Euclidean distance d_k between the curve point P_k and the chord, as shown in Figure 2, which is proportional to the value of the curvature modulus at this point.

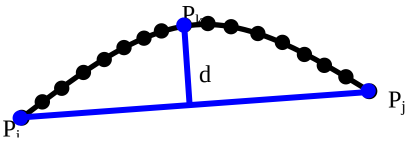

Fig. 2. Fragment of curve Γ with point P_k and chord (P_i, P_j)

After obtaining the contour function, we normalize it with respect to its' maximum value.

3. ACCURACY CONTROL METRICS

Thus, we have a normalized contour function r, calculated using the points of the object perimeter, defined on the set of points $G = \left[0, 360^{\circ}\right]$, and taking a finite number n of values from the domain of variation $\left[0,1\right]$. The full definition of contour functions (***r***-functions) and methods of identifying objects on their base are presented in [10, 13], and an example of contour functions for gear is shown in Figure 1.

To ensure the necessary accuracy control of the detail shape, e.g., the shape of a gear tooth, we construct an array of metrics values, each of them will determine the distance between the sample of contour function and a fragment of the contour function with the number of points corresponding to the sample.

As a sample, we take a section of a contour function defined as: $Q = [\tau_l, \tau_k], Q \subset G, m = k - l$, where ***m***-is the size of the contour function fragment; in the present case in can be one or two teeth of the gear, as shown in Figure 3. On Figure 4 show interactive process selecting part of contour function.

To construct identification metrics, we complete the object set with m points chosen as follows: $G^* = \{t_0, t_1, \ldots t_N, t_0, t_1, \ldots, t_m\}$,

i.e., we add to the end of the array its beginning fragment consisting of m points.

To compare the sample sequence Q and the fragment of the object sequence $G_k^* = \{t_k, t_{k+1}, \ldots t_{k+m}\}, k = \overline{0, \mathrm{m}}$ in the classical DTW method a matrix of distances (deformations) $D(i, j)$ with the dimension $m \times n$ is constructed, where each element (i, j) of the matrix represents a certain distance $d(q, c)$ between two points q_i and g_i. As a rule, this distance is calculated as a Euclidean:

$$d(q_i, g_i) = (q_i^2 - g_i^2)^{1/2}, \qquad (1)$$

but can be also a norm $d(q_i, c_i) = | q_i - c_i |$ [11].

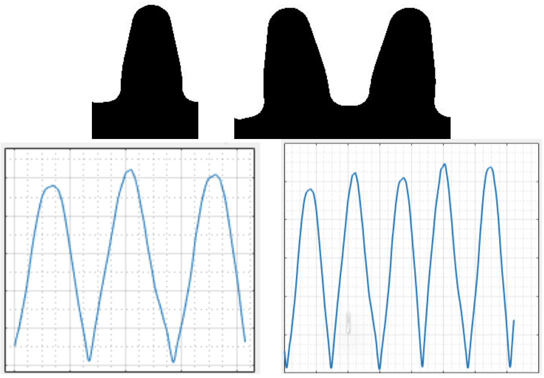

Fig. 3. Image of one and two teeth whose shape us used for reference (top) and its contour functions

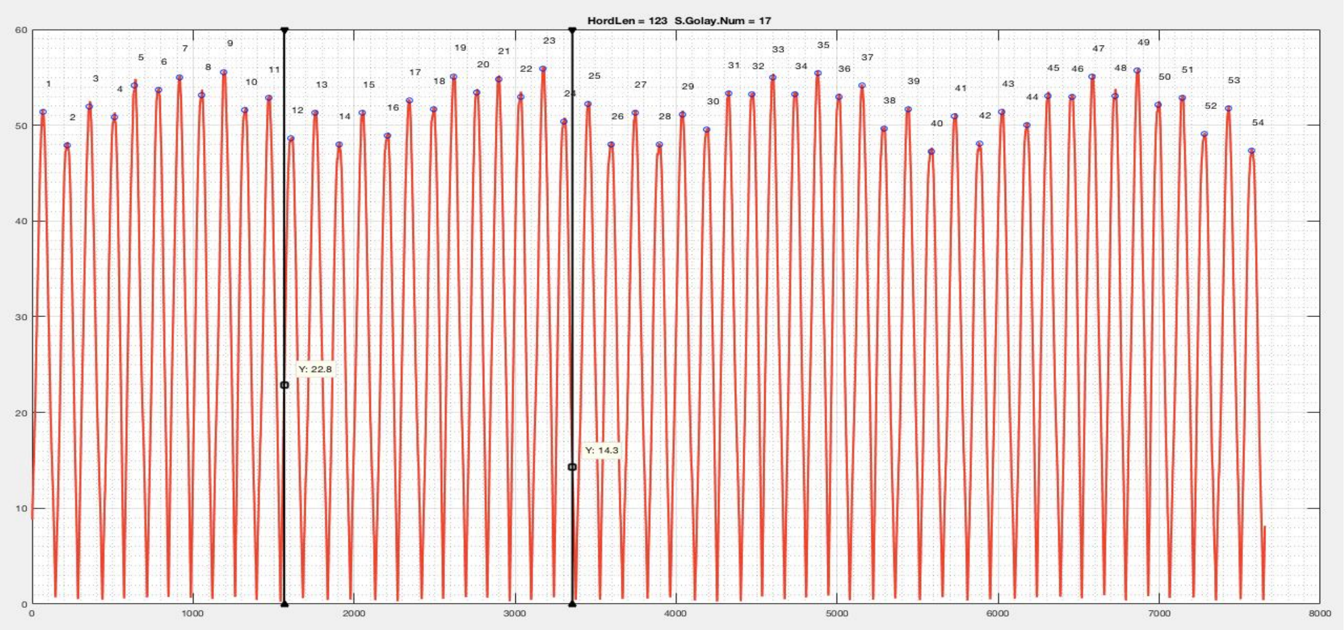

Fig. 4. Interactive process selecting part of contour function for using it as sample. Black vertical line can interactive move for select interest fragment

Each element of the matrix corresponds to a flattening segment between the points q_i and g_i. The aim of the DTW algorithm is to construct a path $W = w_1, w_1, \ldots, w_k, \ldots, w_K$ such that $\max(m, n) \le K < m + n - 1$ under the following limitations:

- *The boundary conditions*: the initial and final points of the matrix diagonal are $w_1 = (1,1)$ and $w_K = (m, n)$.
- *The continuity condition*: for any adjacent points $w_k = (a, b)$ and $w_{k+1} = (a', b')$, it is necessary that $(a - a') \le 1$ and $(b - b') \le 1$.
- *The monotonicity condition*: for any adjacent points $w_k = (a, b)$ and $w_{k+1} = (a', b')$ it is necessary that $(a - a') \ge 0$ and $(b - b') \ge 0$.

From the theoretical manifold of possible paths, the following one is chosen:

$$DTW(Q, G_k^*) = \min\left(\sqrt{\sum_{m-1}^{M} w_m} \Big/ M \right) \qquad (2)$$

In equation (2) the divisor M is used to normalize the metrics value. This path is sough for based on dynamic programming using the formula:

$$\gamma(i, j) = d(q_i, g_j) + \min\{\gamma(i-1, j-1), \gamma(i-1, j), \gamma(i, j-1)\} \qquad (3)$$

where $\gamma(i, j)$ is the accumulation path length and $d(q_i, g_i)$ is the path length from the initial point to the point (i, j). As a result a certain number is obtained that characterizes the distance between the sequences Q и G_k^*, which we will below denote as ρ_{dtw}.

Since the sample sequence length is smaller than the total length of the object sequence, we will calculate the distance with the step 1, each time calculating the value of the metrics ρ_{dtw} on a fragment of the object sequence G_k^* with the length of $\boldsymbol{m}$ points. Repeating this operation $\boldsymbol{N}$ times, we arrive at a sequence of metrics values $\Theta = \{\rho_i, i = 1, N\}$, calculated for each position of the sample with respect to the object. The plot of Θ is shown in Figure 5.

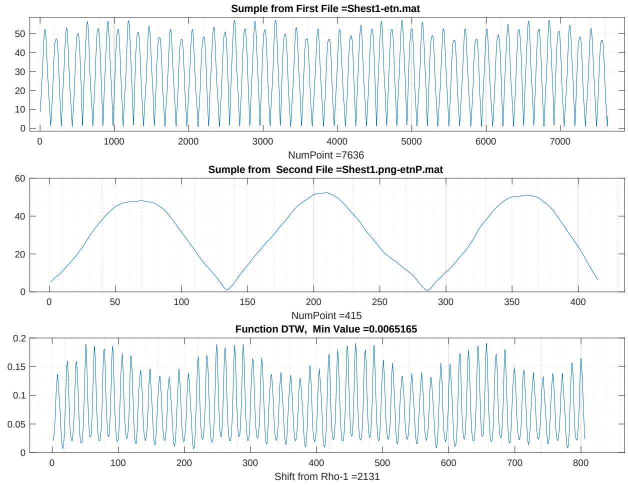

Fig. 5. Plot of the object contour function (top), stretched plot of the reference contour function for one tooth shown in Figure 3 (middle), and the function of metrics values (bottom)

The minimum values of the metrics will correspond to the positions in which the fragment of the contour function of the sample tooth will coincide with the current position of the contour function of the tooth of the controlled gear.

As can be seen from the plot, the values of the metric have oscillations with a frequency equal to twice the number of teeth. This is because when calculating the contour function of an object using the ArcHeight method, the values obtained are proportional to the curvature of the scanned contour. Considering the shape of the gear tooth, it is easy to notice that the curvature growth is observed in two cases - one when moving “up”, the other “down” along the tooth. Since the distance calculated by this method cannot be negative, as a result we obtain the curvature modulus and, therefore, we have maxima and minima twice for one tooth (Figures 3 and 5).

It is easy to see that in the absence of deviations of the shape of the object from the reference, the minima must be primarily at the same level. Some variations of the minimum values noticeable in Figure 5 are due to the discreteness of the contour function and a certain amount of noise caused by the finite dimension of the calculations. When the shape of the object (in this case, the shape of the tooth) deviates from the given (sample) one, the values of the minima increase.

When determining the value of shape errors, it is necessary to know, what values of the minima are acceptable. For this purpose, let us select from Θ a set of minima $Min(\Theta)=\left\{\rho_i^{\min}, i=\overline{1,2*N}\right\}$ and calculate their mean value $M(Min\Theta)$ and variance $D(Min\Theta)$.

Now it is possible to obtain the identification set of points, at which the shape errors exceed the specified classification tolerance using the formula:

$$\lambda(i)=\begin{cases}0, \rho_i^{\min}<(M(Min\Theta)+a\cdot D(Min\Theta))+\varepsilon\\ 1, \rho_i^{\min}\geq(M(Min\Theta)+a\cdot D(Min\Theta))+\varepsilon\end{cases}, \ i=\overline{1,2N} \quad (4)$$

where $\rho_i^{\min}$ is the value of minima of DTW metrics, ε is the classification tolerance (CT) for the considered method, and ***a*** is a certain correction coefficient determined experimentally depending on the conditions of receiving the contour function.

The set $\Lambda=(\lambda_i, i=\overline{1,t})$ will be empty, if the studied object has no shape deviations exceeding the specified classification tolerance. Otherwise, we get a set of values that characterize the positions where the deviations of the required geometry take place.

For example, Figure 6 shows a fragment of the tooth defect. The values of the minimum that exceed the specified classification tolerance level are marked.

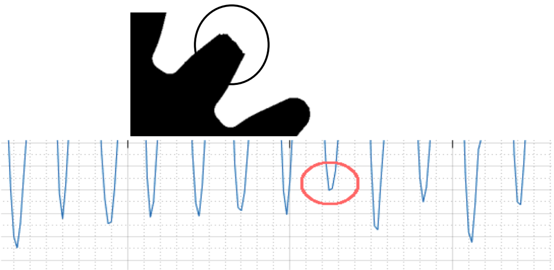

Fig. 6. A fragment of the object with tooth defect (top) and a fragment of the contour function plot with the marked minimum exceeding the classification tolerance (bottom)

4. PROJECTIVE DISTORTIONS

The process of controlling the shape of detail manufactured by the mass method requires a high speed of shape control. When moving the manufactured detail on the conveyor, their deviations from the axial line of movement are possible as shown in Figure 7. This leads to small projective distortions in the shape of the scanned detail. While the methods described in [10] are invariant to affine distortions, small projective distortions lead to errors, i.e., a false attribution of the detail to foul-up and economic loss. The proposed methods allow controlling the shape of an object invariant to small projective distortions when the controlled object deviates from the axis of the conveyor movement.

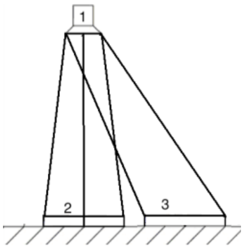

Fig. 7. Deviations of the control object from the axial line. 1 - camera, 2 - normal position of the control object, 3 the object position giving rise to projective distortions of the image

To estimate the degree of influence of projective distortions on the value of the metrics, let us calculate the mean value of the metric minima $M(Min\Theta)$ under the increasing projective distortions.

Figure 8 shows projective distortions of the object, its contour, and the contour function, calculated for such distortions, and Figure 9 illustrates the minima values (magnified) of the calculated DTW metrics.

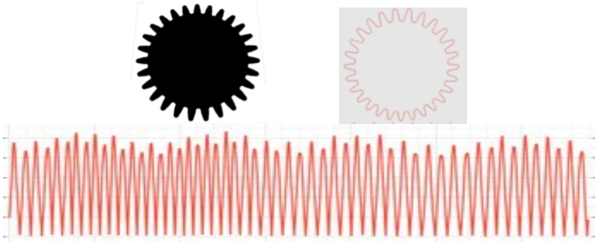

Fig. 8. Projective distortion of the object, its contour and the contour function

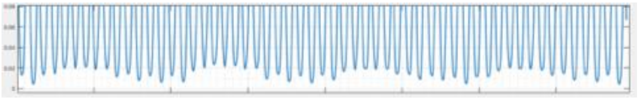

Fig. 9. The minima of the calculated DTW metrics (fragment, zoomed)

As a result of the experiments, it is easy to notice that with projective distortions the values of the minima of the DTW metric increase slightly compared to previous experiments. This dependence of the mean metric values on the magnitude of projective distortions is shown in Figure 10. However, despite this fact, using equation (4), we can calculate the classification tolerance values taking into account the increasing mean values.

Therefore, we can assume that with small projective distortions of the object, the quality control of the shape of the object will remain the same [16].

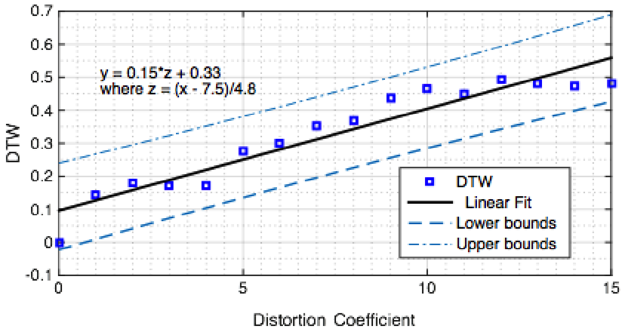

Fig. 10. Dependence of the mean metric values on the magnitude of projective distortions

5. DISCUSSION

It is obvious that the proposed methodology for controlling the shape of the surface of the gear transmission is not directly applicable to all types of gears. However, with some modification of this technology, which consists in positioning the objects of control relative to the camera, it is possible to extend this technology to cylindrical gears with helical gears and bevel gears with straight and curved teeth and even to hypoid and spyroid gears with straight and oblique teeth. Also, when modifying the methodology, so that the object is placed on a support with a change in its position (for example, rotation) relative to the camera, it is possible to control the geometry of worm shafts and gear racks with straight and oblique teeth [17-19].

Recently, in engineering and especially in the automotive industry, new methods of manufacturing detail based on non-tooling of work pieces are actively used. These methods use technologies for the manufacture of detail by casting, stamping, and especially in recent times - the manufacture of detail on 3-D printers.

Consider possible violations of surface geometry in the first case. When preparing the liquid fraction of the injection mass, microbubbles may form. If they get into the injection mold, the surface of the detail in the form of chips and shells may be violated. The second possible defect is an oil leak in the hydraulic cylinders of the injection molding machine, which leads to an incomplete injection mold due to insufficient advancement of the plunger or the required pressure. Here surface distortions are possible in the form of insufficient sizes of small elements of the casting object. Distortion of the shape of parts during stamping is possible with wear on the shape of the stamp and defects in the work pieces.

While manufacturing the details on 3-D printers, various defects are also possible. For example, in the manufacture of detail by the SLS method [20], their surface has a granular structure and requires subsequent heat treatment. Because of this, details manufactured using this technology are subject to shrinkage and distortion of the surface geometry, and their shape may have chips due to loosely sintered tiny grains during printing. When using the FDM technology (layer-by-layer deposition of plastic) [21], micro-sagging of the surface is characteristic, which occurs when temperature fluctuates during printing.

After manufacturing a detail, all these methods require both verification of its shape and control of manufacturing accuracy. For small-scale production, the use of contact methods of such control is ineffective, both in time and in cost. The use of complex non-contact methods, such as interferometric, is too expensive. Therefore, the proposed technology despite certain disadvantages can be considered preferable.

In addition to controlling local distortions by this technology, it is possible to control the global deformations of the details shown in Figure 11.

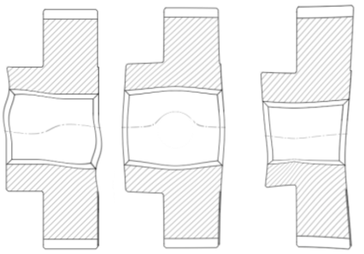

Fig. 11. Deformation of gears during heat treatment (Strongly exaggerated)

This type of distortion occurs during hardening and tempering of metal details and details made on 3D printers using the SLS method. The process of diagnosing distortion will be similar to the stated methodology. To control distortion, objects will need to be positioned relative to the camera in the desired projection.

6. CONCLUSIONS

The considered methods for controlling the quality of the shape of objects using the example of the shape of gear teeth can easily be transferred to controlling the shape of other objects in various fields of mechanical engineering. Their usage does not require large financial costs and the development of special equipment. Another positive feature of such methods is the lack of the need for accurate positioning of objects under the camera, which greatly simplifies the control process. In addition, you must not forget that these methods work in real time, that is, they make it possible to carry out control faster than the process of manufacturing the details. Further development of these methods can be extended to surface quality (roughness) control, as well as to the combination of these methods with others.

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