Surface roughness estimation by using a 3D model reconstructed from multiple images

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Abstract. In this paper, the roughness parameters of the part are estimated based on its reconstructed 3D model. Reconstruction of the 3D model was carried out using the structure from motion photogrammetry method. Preliminary processing of the 3D model consisted in fitting the plane to the point cloud of the 3D model using the least squares method, aligning and scaling the 3D model. Also, the resulting 3D model was approximated using the radially basic functions to obtain a uniform cloud of points. Next, the obtained point cloud was filtered to identify 2D and 3D roughness profiles. As filters, a Gaussian filter and 2RC were used. The roughness parameters of the obtained profiles were calculated. A comparison of the roughness parameters calculated on the basis of the 3D model and the roughness parameters calculated by the BV-7669 profilometer was made.

1. Introduction

In modern engineering one of the most important indicators of the quality of manufactured parts is the quality of its surface, which depends on such characteristics as: roughness, waviness and shape. Surface characteristics can be calculated by contact or contactless methods. Contact methods imply direct contact of a measuring device, for example, a diamond needle of a profilometer with the surface under investigation. Some researchers propose using tribologic methods for surface analysis [1]. This is not always possible or acceptable due to the complexity of the surface of the part or the possibility of damaging its surface upon contact. In paper [2] the authors propose a method of analyzing a liquid drop behavior on the surface. This method is also not always applicable due to various material limitations.

In contactless methods, laser or interference installations are used [3]. However, these optical instruments are expensive and time-consuming to set up equipment. In paper [4], the authors proposed a method of parametrization of a rough surface image based on its information pattern. Also, it is possible to analyse surface roughness by reconstructing a 3D model using matched multiple images [5].

In this paper, is applied method of photogrammetry: Structure from Motion (SFM) [6], for the reconstruction of a three-dimensional model of the part. The use of photogrammetry is convenient...
because it assumes the use of digital photographic equipment, which is currently widely used, has an acceptable price range and is easy to use.

2. 3D model reconstruction

The 3D model was reconstructed using a set of 40 photographs taken using a Canon IXUS 105 camera. In Figure 1, a detail is shown, the axes indicate the number of pixels. The size of each photo is $4000 \times 3000$ pixels. The diameter of the part is 2.8 cm.

For the reconstruction of the 3D model, the Open Multiple View Geometry (MVG) library [7], which implements the SfM method, was used. The Scale Invariant Feature Transform (SIFT) [8] method was used as a key point detector. SIFT uses such descriptors to describe key points that remain unchanged when the image is zoomed and rotated to a certain angle. That is acceptable since it is not supposed to use a tripod for the camera and to maintain a certain distance of the camera lens to the object. It also provides invariance to change the lighting that simplifies the process of shooting. The result of the OpenMVG library is presented in Figure 2.

![Figure 1. Image of the investigated part.](image)

This cloud consists of 3436 3D points. The resulting cloud of points is highly sparse and is not suitable for analyzing the surface of the model. To compile a dense point cloud, the Open Multiple View Stereovision (OpenMVS) [9] library was used that implements the Multiple View Stereovision method. The result of the OpenMVS library is presented in Figure 3.

The resulting three-dimensional cloud consists of 2634154 points. The average distance between the 3D points is 0.002 cm.

3. Evaluation of the surface characteristics of the 3D model

The surface of the part often has a complex shape and relief. The surface structure is isolated on such elements as roughness, waviness, shape, which are shown in the figure 4.
In order to correctly assess the characteristics of the surface, it is necessary to isolate structural elements from the general profile and to evaluate their parameters separately.

3.1 Fitting the plane
The resulting 3D model in three-dimensional space has the position shown in Figure 5.

Figure 3. Point cloud obtained using OpenMVG and OpenMVS libraries.

Figure 4. Structural surface elements.

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3.1 Fitting the plane
The resulting 3D model in three-dimensional space has the position shown in Figure 5.

Figure 5. Spatial position of the 3D model after reconstruction.

Figure 6. The result of fitting the plane to the points of the 3D model.
To fit the plane to the point cloud of the 3D model, the least squares method [10] is used, which is described by the equations:

\[
\begin{pmatrix}
a \\
b \\
c
\end{pmatrix} = (A^T A)^{-1} A^T B; \quad A = \begin{pmatrix} x_i & y_i & 1 \\ \vdots & \vdots & \vdots \\ x_{i+n} & y_{i+n} & 1 \end{pmatrix}, \quad B = \begin{pmatrix} z_i \\ \vdots \\ z_{i+n} \end{pmatrix},
\]

where \(a, b, c\) – coordinates of the normal vector to the plane of fit; \(x_i, y_i, z_i\) – coordinates of 3D model points along X, Y, Z axes.

The result of the fit is shown in Figure 6, where \(n\) is the found normal to the fit plane.

After fitting, the angles of inclination of the normal are calculated using the formulas:

\[
\alpha = \arccos \left( \frac{\vec{n}_{xy} \cdot \vec{x}}{|\vec{n}_{xy}| \cdot |\vec{x}|} \right); \quad \beta = \arccos \left( \frac{\vec{n}_{xz} \cdot \vec{z}}{|\vec{n}_{xz}| \cdot |\vec{z}|} \right);
\]

where \(\vec{n}_{xy}\) – the projection of the normal vector to the XY plane; \(\vec{n}_{xz}\) – the projection of the normal vector to the XZ plane; \(\vec{x}\) – vector parallel to the axis X; \(\vec{z}\) – vector parallel to the axis Z.

The calculated angles are used to rotate the 3D model, after which the normal vector will be parallel to the Z axis. After rotation, you need to scale the 3D model, at which its size will correspond to the actual size of the part. The scale factor is enough to calculate on one of the axes: X, Y, Z. The scaling factor is calculated by the formula: \(k = \frac{L}{S}\), where \(L\) – distance between two points on the surface of the real part; \(S\) – distance between the same points but on the 3D model. The result of rotation and scaling of the 3D model is presented in Figure 7.

3.2 Interpolation and filtering the surface of the three-dimensional model
The reconstructed 3D model is a cloud of scattered points and is not suitable for determining surface characteristics, since points of the surface in any direction are located at different distances from each
other. It is necessary to approximate the initial set of points to move from the 3D model with scattered points to the 3D model, with points that are located at the nodes of the regular grid. In that work for approximation, the method of radial basis functions (RBF) [11], implemented in the Python library: SciPy [12], is used. The smoothing parameter was used, which is 1. Figure 8 shows an example of approximation.

From the set of points of the 3D model, we will select a rectangular area for which we will perform the approximation, the step between the new calculated points along the X and Y axis is 0.0012 cm. The result is shown in Figure 9.

![Figure 8](image_url)

**Figure 8.** Approximation result.

3.3 Filtering

At the filtration stage, information on the structural elements of the surface, such as the wavy profile and roughness profile, is extracted. The main assumption is that the surface profile is a combination of different wavelengths and that certain wavelength bands correspond to certain structural elements of the surface. The task of filtering is to select from the general profile a set of profiles that correspond to certain wavelength bands. The theoretical foundations of filtering are described in the theory of signal processing. Filtering of surface profiles is mainly carried out through the operation of discrete convolution of the heights of the original profile and the so-called weighting functions - the filter. The one-dimensional convolution formula has the form:

\[ z_2(n) = \sum_{i=0}^{P} s_i z_1(n - i), \]

where \( A = 3.64 \) - a constant providing 75% attenuation of the amplitude of a wave whose length is equal to the cut-off wavelength.

\( z_2(n) \) - heights of profile points after filter action;
\( z_1(n) \) - the height values of the points of the original profile;
\( s_i \) - weight function values;
\( P \) - filter size.

For filtering were used filters such as filter Gauss and 2RC [13]. The 2RC one-dimensional weight function is:

\[ S(r) = \frac{A}{\lambda_c} \left( 2 - A \frac{|r|}{\lambda_c} \right) \exp \left( -A \frac{|r|}{\lambda_c} \right), \]

where \( r \) - the position of the point relative to the beginning of the weight function; \( \lambda_c \) - cut-off wavelength.

The one-dimensional Gaussian weight function is:

\[ S(r) = \frac{1}{\alpha \lambda_c} \exp \left( -\pi \frac{r^2}{\alpha^2 \lambda_c^2} \right), \]

where \( \alpha = \sqrt{\ln 2/\pi} \) - constant providing 50% attenuation of the wave amplitude whose length is equal to the cut-off wavelength.
Perform filtering of the initial profile with Gaussian and 2RC filters. According to the ISO 16610-21:2011 [14] recommendation, we take the cut-off wavelength: $\lambda_c = 0.025$ cm. Figure 10 shows the Gaussian weight function on the left, and 2RC on the right. Figure 11 shows the result of filtering as a result of which the mean waviness lines were found.

![Figure 10. Gaussian and 2RC weight functions.](image)

Figure 11 shows a noticeable deviation of the 2RC line of waviness from the initial profile, which is a drawback of this filter and is due to the non-periodicity of the initial profile. Having calculated the deviation of the initial profile from the mean lines waviness, we obtain the roughness profiles shown in Figure 12.

![Figure 11. Filtering result with Gauss and 2RC filters.](image)

For 3D filtration of the surface, a two-dimensional Gaussian weight function is used, which is given in the form:
where \( \lambda_{xc} \) and \( \lambda_{yc} \) are cut-off wavelengths.

Figure 13 shows the two-dimensional Gaussian weight function with \( \lambda_{xc} = \lambda_{yc} = 0.025 \text{ cm} \).

\[
S(x, y) = \frac{1}{\sigma^2 \lambda_{xc} \lambda_{yc}} \exp \left[ - \left( \frac{x}{\sigma \lambda_{xc}} \right)^2 - \left( \frac{y}{\sigma \lambda_{yc}} \right)^2 \right],
\]

As a result of the convolution of the two-dimensional weight Gaussian functions with the initial profile, the mean waviness surface was found. A fragment of the surface is shown in Figure 14.

Figure 13. Two-dimensional Gaussian weight function.

Figure 14. Mean surface of waviness.

Having calculated the deviation of the heights of the original surface from the heights of the mean surface of waviness, we obtain a map of the heights of the roughness surface, presented in Figure 15.

3.4. Parameterization

Profiles extracted using filtering represent factual quantitative information, the parameters of which are used to assess the functionality of the surface and its quality. Consider some surface parameters [15]:

\[
R_a = \frac{1}{n} \sum_{i=1}^{n} |r(i)|
\]

- arithmetic mean deviation used as a general roughness amplitude estimate. Where \( n \) - number of profile points; \( r(i) \) – deviation from the midline.

\[
R_z = \frac{1}{5} \sum_{i=1}^{5} |m_i| + \frac{1}{5} \sum_{i=5}^{n} |v_i|
\]

- the sum of the average absolute values of the heights of the five largest protrusions of the profile and the five largest depressions of the profile. Where \( m_i \) – height of the i-th largest protrusion, \( v_i \) – depth of the i-th largest depression of the profile.
4. Results

For comparison, the evaluation of the roughness parameters of the part shown in Figure 1 was carried out using a БВ-7669 profilometer. The measurement step of the profilometer was 1.2 μm, the total number of points analyzed by the profilometer is 8700. The profile obtained on the basis of the 3D model has 1001 points with a step of 12 μm. The calculated roughness parameters are presented in table 1.

Table 1. Calculated roughness parameters.

| Data source     | Filter | $R_a$, μm | $R_z$, μm | $R_p$, μm | $R_v$, μm |
|-----------------|--------|-----------|-----------|-----------|-----------|
| 3D model        | Gauss  | 10.1      | 35.9      | 25.4      | 15.1      |
| 2RC             |        | 58.3      | 225.2     | 200.5     | 150.3     |
| Profilometer БВ-7669 | Gauss  | 2.2       | 22        | 15.6      | 6.01      |

The 2RC filter showed poor results since the mean line of waviness calculated using it has a phase distortion that is a disadvantage of this filter. This filter is not intended to filter profiles with non-periodic waviness. The roughness parameters calculated by the profilometer are more reliable than those calculated on the basis of the 3D model. This is due to the fact that photos taken with the help of Canon IXUS 105 are not sufficiently detailed enough and do not transmit such small profile changes.

5. Conclusion

In the course of the work done, the 3D model of the part shown in Figure 1 was reconstructed from a set of 40 photos of this part. The reconstruction of the 3D model was carried out using the OpenMVG, OpenMVS libraries. A 3D model was pre-processed - a fit, during which it was possible to align the 3D model and scale it. Next, was made of the approximation of a cloud of unstructured 3d points of the model using radial basis functions, as a result of which a uniform cloud of points was obtained. After fitting and approximation, filtering of 2D and 3D profiles was performed. After fitting and approximation, filtering of 2D and 3D profiles was performed. As filters, a Gaussian filter and 2RC were used. As a result of filtering, 2D and 3D waviness profiles were obtained, using which roughness profiles were identified. When comparing the roughness parameters on the basis of models and parameters obtained using a БВ-7669 profilometer, it was found that the detailing of the 3D model is insufficient and the results of the profilometer are accurate. To increase the detail of the 3D model, it is necessary to use more accurate photographic equipment with a higher resolution. Nevertheless, the use of photogrammetric systems for analyzing the characteristics of the surface of a part is advisable due to the lack of contact with the surface, as well as the existence of the ability to analyze the entire part entirely and different methods using a single 3D model.
6. References

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