A three-dimensional measure of surface roughness based on mathematical morphology

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Abstract

In industrial surface characterization tasks, tactile profile measurement instruments are still the dominating tool for measuring surface roughness. Among the parameters for quantifying surface roughness based on tactile profile sections, R_z and R_a are the most popular ones. Nevertheless, it is widely recognized that profile parameters in general should be replaced by parameters which use the whole surface information made available by state of the art 3D-measuring devices like white-light interferometry. In this contribution, a natural and easily interpretable extension of the roughness characteristic R_z for 3D data, called S_z^{morph}, is proposed and its intimate relation to the volume scale function, a fractal characteristic recently proposed for standardization, is shown. The derivation shows that while the slope of the volume scale function gives an indication of local fractal dimension, its absolute value is closely related to traditional definitions of surface roughness. The proposed characteristic ignores surface directionality and as such is applicable to directional and non-directional surfaces. Experimental results for three different technical surfaces demonstrate the very good correlation of S_z^{morph} with the original parameter R_z.

1 Introduction

In the development and production of industrial parts, both the macroscopic shape and the microstructure of the surface on a μm-scale strongly influence the parts' properties. For instance, surfaces in frictional contact should be structured in a way to reduce the expected wear by optimizing their lubrication properties. A gasket surface must not be too rough to prevent leakage, etc.

The measurement of surface roughness started a few decades ago with the advent of tactile profilometers. These drag a stylus along a line segment and record the vertical deflection of the stylus as it moves over the surface, thus recording the height of the surface at the sampling points. One disadvantage of such a tactile measurement is that the stylus has to stay in permanent contact with the surface and is therefore easily damaged or soiled. Furthermore, the single profile line covers only a small part of the surface, possibly missing important areas.

In recent years, large efforts have been made to establish 3D-measuring instruments which can acquire a 3D-height map at once. Common techniques include white-light interferometry or fringe projection. Their operation is contactless and fast, thus fulfilling the requirements for the application in an industrial environment.

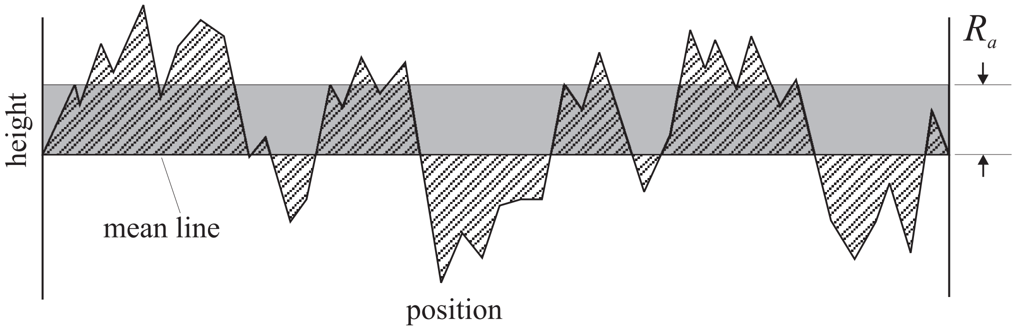

Figure 1: Calculation of the profile roughness parameter R_a. The hatched area under the curve equals the area of the gray rectangle.

While theoretical advances towards a characterization of 3D surface texture have been made [1, 2], culminating in a proposal for a new ISO standard for 3D surface characterization [3], in practice the evaluation of the acquired data is often still based on the parameters developed for tactile 2D-measuring instruments: even if a complete 3D data set is available, roughness characteristics are calculated from a set of intersecting or parallel 2D line segments.[1]

When it comes to specifying the roughness of technical surfaces, R_z and R_a are the most common choices [4]. R_a is the mean absolute deviation from zero of the high-pass filtered profile (figure 1). R_z is defined as [5]

$$R_z = \frac{\sum_{i=1}^{5} R_{z_i}}{5}. \tag{1}$$

R_{z_i} are the vertical distances between the highest peak and the lowest valley in each of five consecutive line segments l_r of a high-pass filtered profile. Accordingly, R_z is an extreme value statistic which summarizes extreme valleys and peaks (figure 2).

Obviously, the methods developed for 2D profiles do not fully exploit the information available in a 3D measurement, and new areal descriptors should be used.

Recently, a new standard for areal surface texture characterization has been proposed [3], which offers a replacement of the old R_z by S_z^{10}. S_z^{10} is the ten point height of the surface, expressing the difference between the ten highest peaks and ten lowest pits on the filtered surface. In contrast to R_z

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[1] Unfortunately, the extraction of a profile segment itself from a matrix of height values requires interpolation if the sampling points of the line do not match the grid given by the matrix, which will yield a distorted profile.

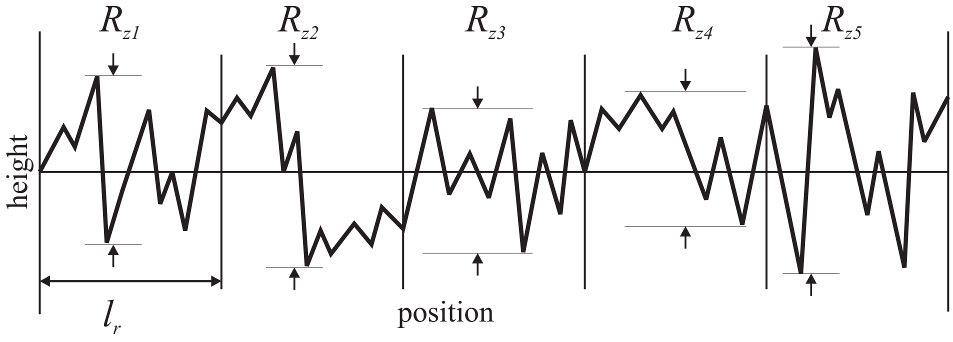

Figure 2: Calculation of the profile roughness parameter R_z.

(fig. 2), which simply evaluates maxima and minima on the distinct line segments, S_z^{10} is based on peaks and pits which can be located anywhere on the surface. The extraction of the relevant peaks and pits is not an easy task [6], but can be accomplished with advanced computing techniques [3, 7].

S_z^{10} generalizes the definition of an extreme value characteristic based on the five highest peaks and five lowest pits of a roughness profile. As such, it is susceptible to outliers.

2 A Generalization of R_z to 3D

The first step towards a generalization of R_z is to drop the requirement of non-overlapping line segments. Instead, the line segment l_r can be shifted over the whole profile. Similar to eq. 1 the vertical distance between the highest peak and the lowest valley on the line segment l_r shifted by i sampling points is denoted as R'_{z_i}. If l_r consists of M measured amplitudes from a total of N amplitudes $p_1, \ldots, p_N$ which are spaced with $\delta = \frac{l_r}{M-1}$, this yields

$$R'_{z_i} = \max\{p_{i+1}, \ldots, p_{i+M}\} - \min\{p_{i+1}, \ldots, p_{i+M}\}. \tag{2}$$

R'_z then can be defined as the mean over all R'_{z_i}:

$$R'_z = \frac{\sum_{i=0}^{N-M} R'_{z_i}}{N - M + 1}. \tag{3}$$

Now it is not a big step to generalize R_z further. When moving from a 2D measurement to a 3D measurement, averages analogous to eq. 3 can be calculated by shifting the line segment not only along the profile, but over the whole measurement area. However, the calculation of R'_{z_i} from amplitudes along a line segment is no longer adequate. If the surface is non-isotropic, the outcome of eq. 3 strongly depends on the direction of the segment. It is possible either to take the mean over all directions, in which case it is necessary to interpolate the data on the grid or, better, to choose a support for R'_{z_i} which does not emphasize a certain direction. The most isotropic generalization of a 1D line segment to 2D is a disc, and therefore R'_{z_i} in eq. 3 is replaced by $S_{z_{kl}}$, the vertical distance between the highest peak and the lowest valley on a disc of radius r located at grid position kl.

The formula corresponding to eq. 3 for an $N \times M$ height map becomes

$$S_z^{morph} = \frac{1}{(N-2r)(M-2r)} \sum_{k=r+1}^{N-r} \sum_{l=r+1}^{M-r} S_{z_{kl}} \tag{4}$$

To compute S_z^{morph} according to eq. 4, for each grid point of the height map, the maximum and the minimum amplitude in the disc centered on that grid point have to be found. Then, the two resulting matrices are subtracted and the mean over all values is taken, which gives S_z^{morph}.

The original R_z can yield different values depending on the direction of the underlying line segment. Since S_z^{morph} is based on a rotation-invariant structuring element, it is not influenced by surface texture directionality and can thus be applied to surfaces with and without directional texture. On the other hand, it is not possible to investigate surface texture directionality using S_z^{morph}.

The task of finding local minima and maxima can be implemented by means of the well-known dilation and erosion operators from morphologic image processing [8], using a disc-shaped “structuring element” if radius r (figure 3). The difference between the dilated and the eroded images is called *morphological gradient* [9]; accordingly, S_z^{morph} as defined in eq. 4 is denoted as *morphological* S_z.

Thus a surface roughness parameter has been related to an established morphological image operator that is available in many image processing packages.

S_z^{morph} is closely related to the volume scale function S_{vs} defined in [3, 10]: The volume scale function is the volume between a morphological closing and opening of the surface using square structuring elements of various sizes (figure 4). Except for the shape of the structuring element, S_z^{morph} is nothing but the value of S_{vs} at a given scale, divided by the evaluation area. A difference is that the proposed standard [3] suggests evaluating the derivative of the volume scale function S_{vs} with respect to the the scale, whereas the above derivation of S_z^{morph} reveals that the absolute value of the related S_z^{morph} is also informative.

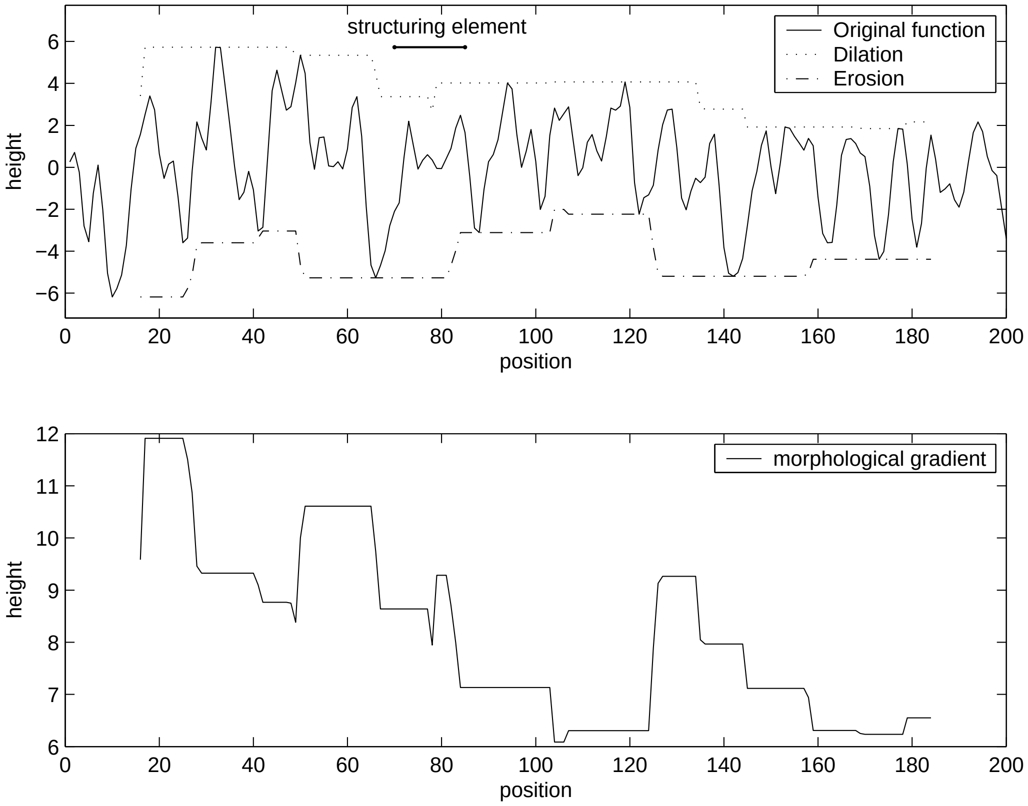

Figure 3: Dilation and erosion of a 2D-function with a given structuring element (top) and the morphological gradient calculated from these (bottom). The spatial average of the morphological gradient gives the surface roughness estimate R'_z, see eq. 3.

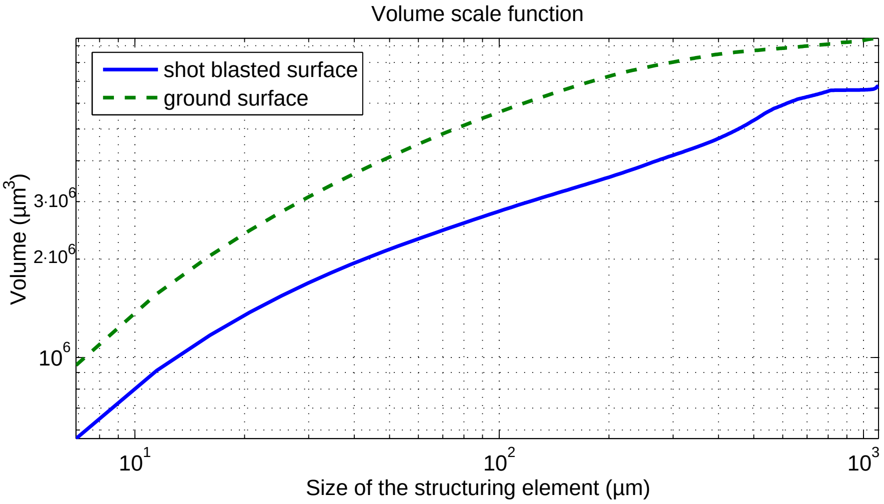

Figure 4: Volume scale function S_{vs} of ground and shot-blasted surfaces (cf. fig. 5). S_{vs} is the volume between a dilation and an erosion of the surface; S_{vs} is plotted as a log-log plot.

The plausibility of this connection is underlined by the use of morphological filters to calculate the upper and lower envelope of a surface [11]. Morphological filter operations similar to those mentioned above have been used to compute envelopes for the analysis of surface roughness [12]. Other applications are the extraction of topological features [13], thus making mathematical morphology an important tool for the analysis of surface data.

3 Experimental setup

To evaluate the performance of the S_z^{morph} defined above, measurements of different technical surfaces were acquired. Ground and two kinds of shot-blasted surfaces (specimen R1 to R7, R8 to R14 and R15 to R20, respectively) with different process parameters (figure 5) were compared; the specimens were characterized using a tactile device (Mahr Perthometer, Göttingen), and a white light interferometer with a pixel resolution of $2.3\mu m$ (Zygo NewView 5000, Middlefield). This pixel resolution was chosen to match the size of the stylus tip of the tactile device. On each specimen, four different regions were measured. Tactile and optical measurements were performed at the same locations on the specimen so that the results could be directly compared.

On the acquired data sets, the following parameters were calculated:

- the tactile R_z according to [5] with a cutoff wavelength of 0.8mm, using

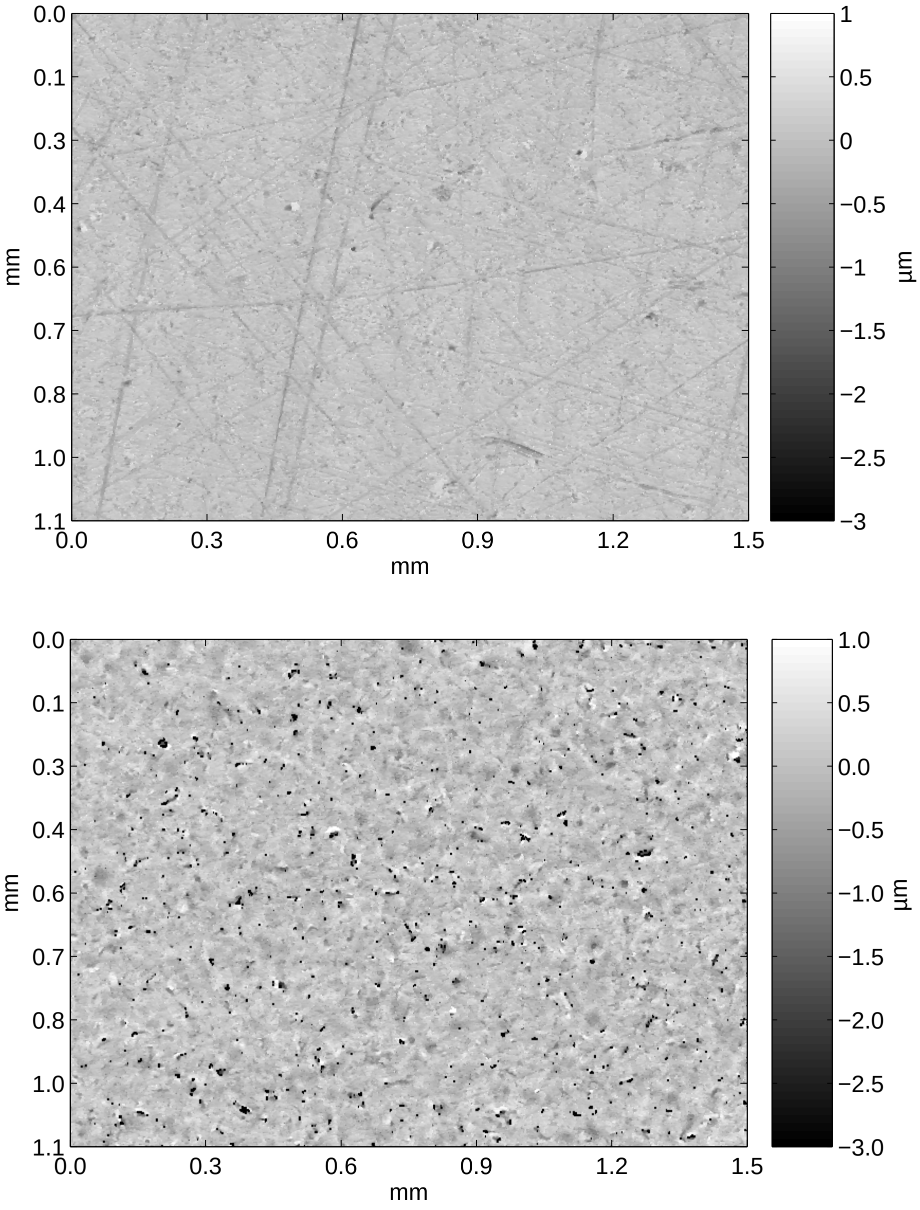

Figure 5: Height maps of a ground and a shot-blasted surface used in the experiments. Black pixels denote missing data.

$l_r = 0.8mm$

- S_z^X, the average over the R_z values in each line of the height map, which was calculated by Zygo's Metropro software [14]
- the S_z^{morph} defined in eq. 4

All optical measurements were filtered with a 3D-Gaussian filter with cutoff wavelength 0.8mm in vertical and horizontal direction.

The shot-blasted surfaces were non-directional. The ground surfaces did exhibit scratches, but these did not show a preferred directionality. Therefore, not only S_z^{morph}, which ignores the surface texture direction by definition, but also R_z and S_z^X are approximately independent of the rotation of the surfaces.

To calculate S_z^{morph}, the radius of the disc-shaped structuring element has to be chosen. Here, for a cutoff wavelength l_r=0.8mm, a radius $r = 10\mu m$ yielded results that best matched the tactile R_z-values.

4 Results and Discussion

The results of all calculations are shown in figure 6. The horizontal axis distinguishes the specimen $R_1, \ldots, R_{20}$. On the vertical axis, the corresponding roughness values are plotted. The lines show the mean of roughness parameters for the four regions on a specimen and the error bars indicate their standard deviation.

The excellent correlation between the S_z^X values obtained from the Metropro software and the morphological S_z^{morph} is immediately obvious from figure 6. On the data sets examined, both methods yield similar mean values and standard deviations. This finding suggests that S_z^{morph} and S_{vs} are adequate for 3D data from optical measurement systems such as white light interferometry.

If 3D parameters are compared to their 2D counterpart, one notices that they have, in general, a smaller deviation. In figure 7, R_z is plotted against S_z^{morph}; each point in the plane corresponds to a tactile R_z– S_z^{morph} pair. Each ellipse represents one specimen, where the orientation and size of the ellipse reflect the spread of the four single measurements. The smaller deviation of the S_z^{morph} values is due to the fact that the S_z^{morph} calculation is based on much more data than is used in tactile methods. Accordingly, outliers have a smaller influence on the calculated parameters.

Fig. 6 also shows a systematic difference between R_z and S_z^{morph}. For a better understanding of the correlation between R_z and S_z^{morph}, a straight

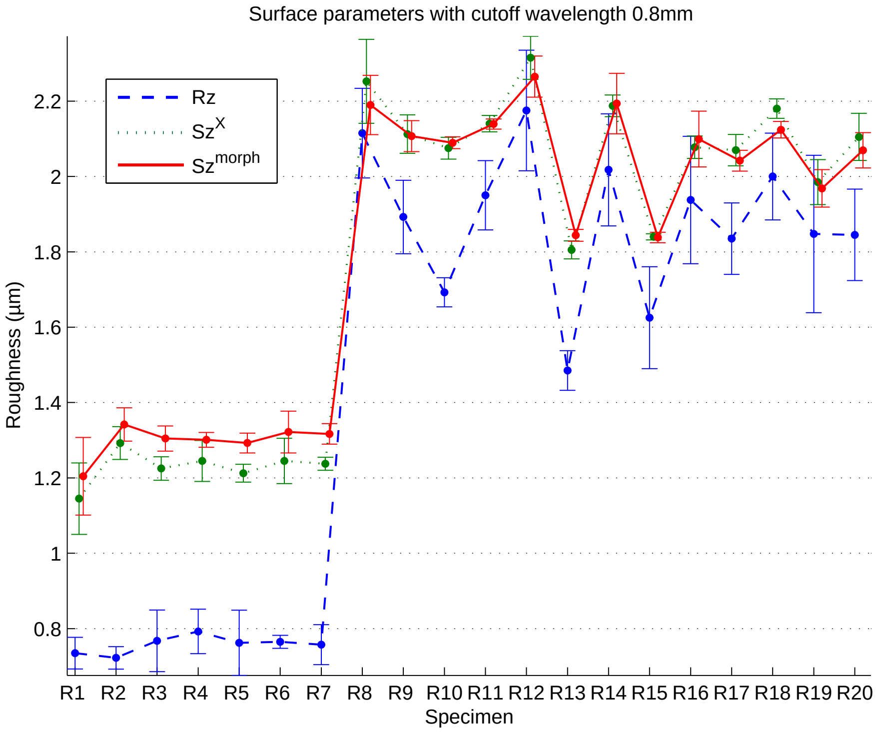

Figure 6: Overview of the roughness parameters obtained for measurements on 20 specimen that underwent grinding (R1-R7) or shot-blasting (R8-R20).

line (dashed line, fig. 7) has been fitted through the R_z-S_z^{morph}-pairs using total least squares [15]. This line shows a small but significant deviation from the straight line through the origin with slope 1 (dotted line). This finding can be explained by outliers found in data acquired with optical measurement instruments [16]. As S_z^{morph} is an extreme value statistic, these outliers cause the trend to values higher than those expected from the tactile R_z-measurements.

5 Conclusions

A generalization of the popular surface roughness characteristic R_z to 3D measurement data has been proposed. The resulting parameter, S_z^{morph}, is closely related to the volume scale function. Both characteristics can easily be calculated from the image processing operator "morphological gradient" which gives the difference between the upper and lower local envelopes of a surface. Since these envelopes effectively determine properties such as sealing or accuracy of assembling, both volume scale function and S_z^{morph} are plausible descriptors for these functionalities. S_z^{morph} is isotropic and can therefore be applied to directional and non-directional surfaces without the need for choosing an evaluation direction. Its good correlation with the tactile R_z qualifies it as a possible generalization of R_z for surface height data.

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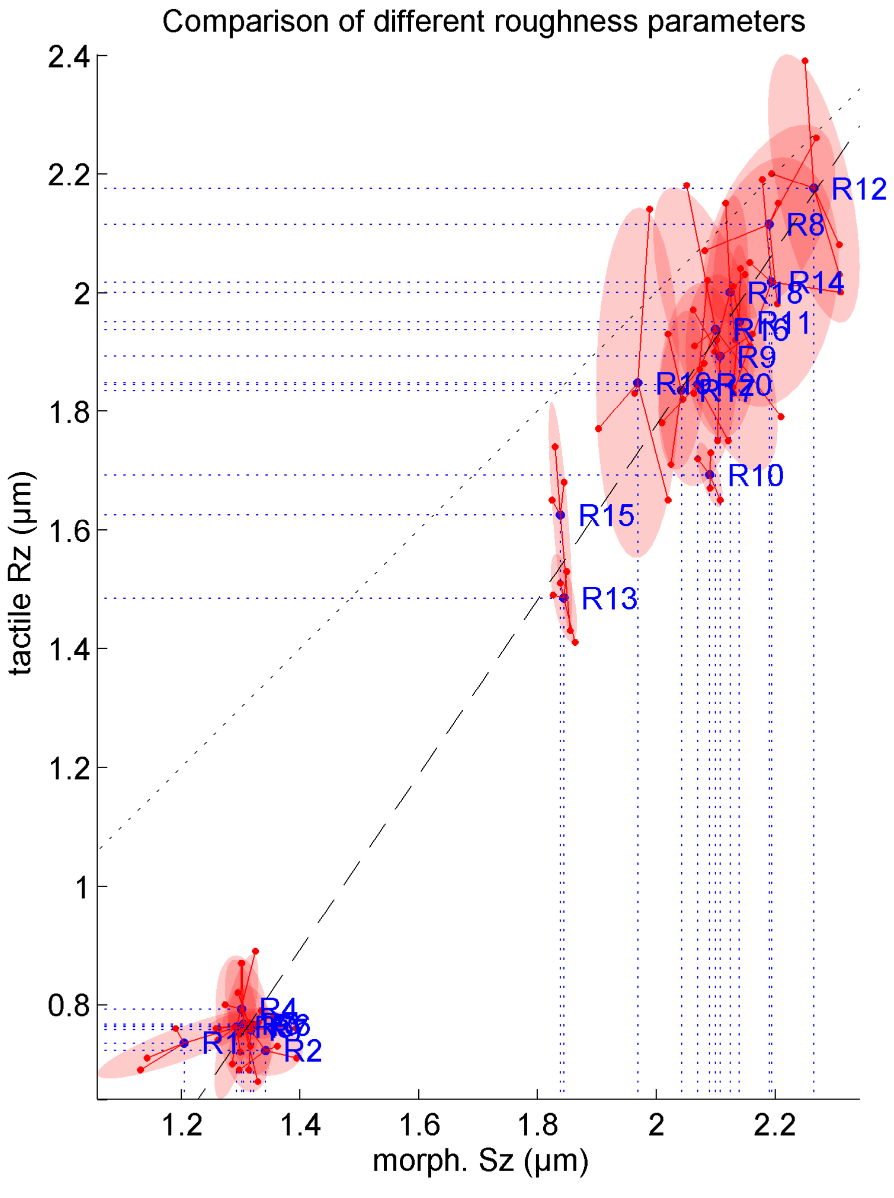

Figure 7: Relation between different parameters from tactile and optical measurements.

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