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Surface image enhancement and discrimination with the application of wavelet decomposition

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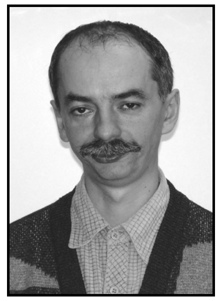

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Abstract

A digital image of a machined surface consists of numbers describing the reflection of light from the surface. In this paper there is presented a method of image processing for emphasizing the features of surface roughness. It is based on the properties of the Wavelet Transform to detect the presence of details which are usually lost when other methods of noise reduction are applied. A universal image quality index UIQ for loss of correlation, luminance distortion, and contrast distortion was used to measure objective image quality loss when image processing was applied.

Keywords: discrete wavelet transform, machined surface image, image processing.

Zastosowanie dyskretnej transformaty falkowej do redukcji zakłóceń w obrazie powierzchni obrobionej

Streszczenie

Dla metody monitorowania powierzchni obrobionej, opracowanej w Zakładzie Monitorowania Procesów Technologicznych Politechniki Koszalińskiej, podstawowym źródłem informacji jest obraz cyfrowy tej powierzchni [1-3]. Każda zmiana warunków pozyskiwania i przetwarzania obrazu wpływa na dokładność i wiarygodność wyników. Wskazane jest, zatem, ujednolicenie procedur przetwarzania obrazu przy zachowaniu poziomu informacji na tym samym poziomie [4]. Obraz powierzchni obrobionej w postaci cyfrowej reprezentowany jest macierzą liczb, będących odzwierciedleniem stanu odbicia światła od tej powierzchni. Światło odbijając się od powierzchni powoduje tworzenie obrazu śladów obróbki o wyraźnym ukierunkowaniu. W artykule prezentowana jest metoda przetwarzania obrazu powierzchni obrobionej w celu podkreślenia w nim cech chropowatości powierzchni przy jednoczesnej redukcji zakłóceń wynikających ze zmiennych warunków pozyskiwania obrazu. Prezentowana procedura przetwarzania obrazu wykorzystuje własności transformaty falkowej [5-13], dzięki której istnieje możliwość wyróżnienia szczegółów obecnych w obrazie na tle głównego motywu tekstury, w tym przypadku śladów po przejściu narzędzia. Metoda zapewnia pozostawienie szczegółów, które zwykle ulegają usunięciu lub niekorzystnej zmianie przy filtracji obrazu.

Słowa kluczowe: dyskretna transformata falkowa, obraz powierzchni obrobionej, przetwarzanie obrazu.

1. Introduction

A machined surface is the result of selection of the process parameters. Numerous uncontrollable factors influence its state. Estimation of surface quality during the manufacturing process is subject to a great deal of limitations. When a vision system is applied to the process of measuring surface finish, it is possible to perform the task with a short time of acquisition and simultaneous processing of imaging data. The system also has the advantage that it is a non-contact, remote and non-destructive method of measurement [1].

The vision system software is based on a collection of image data, on whose content the processing relies. In turn, the features of the machined surface image depend on the properties of a workpiece, a tool and cutting conditions [2-3].

This paper presents a method of digital image processing to enable the elimination of machined surface interference resulting from variable lighting conditions, and to highlight the image features arising from the roughness of the observed surface. The method of surface image quality improvement is based on the Discrete Wavelet Transform properties, whereby it is possible to separate different components contained in the measured signal. First the image quality, noise and blur are defined, and then the two-dimensional Discrete Wavelets Transform and a procedure of image processing are introduced. As a result of the research it was decided to perform three corrections to the measured image: to remove noise, to enhance important details, and to make an adjustment of image brightness. Finally, the contribution of the applied transformations to quantitative change in the measured image is evaluated using a universal image quality index (UIQ), and a general procedure of image processing in the wavelet domain is proposed.

2. Definition of the problem

In metrology an image system must be sensitive to real data. Factors such as object roughness, reflectivity variations, non-uniform illumination, aberrations, shot noise and CCD noise cause deterioration of the image and reduce its usefulness in further processing. The blur or degradation of an image can be caused by movement during the image capture process, out-of-focus optics, use of a wide-angle lens, atmospheric turbulence, or a short exposure time, scattered light distortion or other factors.

For image processing, it is important to compare the image quality before and after data processing. So the definition of a similarity measure of images and quality assessment becomes a key issue. The quality (similarity) measure must satisfy the condition of symmetry, boundedness and unique maximum. In the Universal Image Quality index (UIQ) proposed in [4], three components are combined to describe the similarity of two images A and B, namely: loss of correlation, luminance distortion, and contrast distortion:

$$\mathrm{UIQ} = \frac{\sigma_{AB}}{\sigma_A \sigma_B} \cdot \frac{2\mu_A \mu_B}{\mu_A^2 + \mu_B^2} \cdot \frac{2\sigma_A \sigma_B}{\sigma_A^2 + \sigma_B^2}, \tag{1}$$

where σ_{AB} is the covariance between A and B, μ_A, μ_B are the mean brightness values for images A and B, and σ_A, σ_B are the mean standard deviation values for images A and B. The dynamic range of UIQ is $\mathrm{UIQ} \in \langle 0,1 \rangle$. When two images are identical, then $\mathrm{UIQ} = 1$.

2.1. Deblurring

An image – blurred or degraded – can be described by the equation

$$g = H\,f + n\,, \tag{2}$$

where g denotes the blurred image, H the distortion operator (the point spread function PSF), f the original true image, and n the additive noise (Fig. 1).

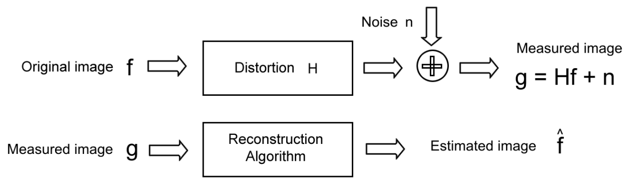

Fig. 1. Estimation of deblurred and denoised image
Rys. 1. Modelowanie procesu poprawy jakości obrazu

The distortion in the image is the result of application of the convolution operation of the distortion operator with the image. Distortion caused by a point spread function (PSF) is responsible for the blur in an image. The point spread function describes in the spatial domain the degree to which an optical system blurs (spreads) a point of light. Deconvolution is the process of reversing the effect of convolution, and the quality of the deblurred image is mainly determined by knowledge of the point spread function. Deblurring is an iterative process. The deblurring process must be repeated with numerous judgments about whether newly uncovered features in the image are features of the original scene or simply artefacts of the deblurring process.

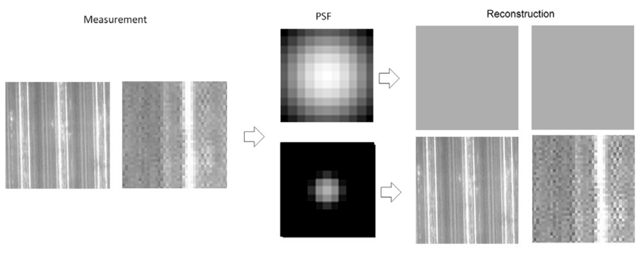

Fig. 2. Deblurring of the measured image with the use of Gauss PSF
Rys. 2. Przykłady usuwania rozmycia krawędzi metodą rozplotu przy zadanej PSF w postaci funkcji Gaussa

Figure 2 shows the result of the deconvolution process – reconstruction of the original image from measurements. Reconstruction results with the assumption of zero noise indicate that deconvolution enhances not only the image features, but also the noise ratio. The deconvolution process introduces ringing artefacts. In digital image processing, ringing artefacts appear as spurious signals near sharp transitions in a signal. Visually, they appear as bands near edges. Ringing in the spatial domain causes ripples or oscillations around sharp edges or contours in the image. Ringing artefacts are the result of signal noise enhancement, so image deblurring must be performed with the simultaneous image denoising.

2.2. Denoising

In image denoising the noise is treated as additive and Gaussian white noise. This is only an assumption. In real applications the noise is usually unknown and may be non-additive. The problem is how to estimate it from an image and then apply it in the same image.

What we perceive as noise depends on the signal. Noise can be defined as anything that does not belong to a certain structure of an image. Considering a single image region with given constant brightness, noise is what stands out from its uniformity (Fig. 3). When an image is divided into regions of certain uniform brightness, and for each of the regions the brightness and the standard deviation are determined, then the standard deviation is the explanation for the image noise, additionally depending on region brightness.

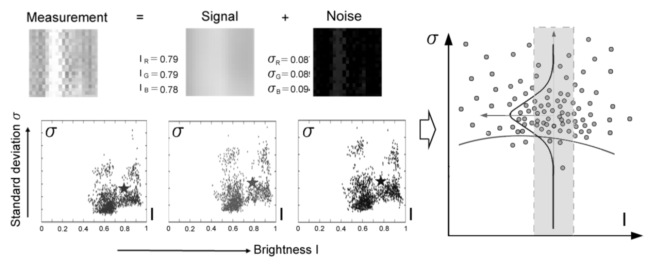

Fig. 3. Estimation of variance distribution of image noise
Rys. 3. Estymacja rozkładu wariancji szumu w obrazie w zależności od jasności

The mean brightness of the area is usually accurately estimated; nevertheless the standard deviation can contain signal, so it is an overestimate. When we want to know the noise level, the lower envelope of the standard deviation distribution is the upper bound of the noise level function.

A measured image g (a noisy image) can be estimated by a noise-free image x corrupted by additive noise n

$$g = x + n\,, \tag{3}$$

where n is white zero-mean Gaussian noise independent of the image x [5-6].

The goal of denoising is to estimate x from the measured image g (noisy observation). The estimate $\hat{x}$ is a function of the measured image ($\hat{x} = \hat{x}(g)$) and the maximum a posteriori (MAP) estimator can be used to determine the most likely value of x.

The MAP estimator is based on the probability density function of x and it determines the value of x where the probability has a peak value. Therefore, the MAP estimator can be defined as

$$\hat{x}(g) = \arg\max_{x} p_{x|g}(x|g)\,, \tag{4}$$

where 'arg max' is the value of the argument where the function has its maximum. The probability density function $p_{x|g}(x|g)$ is the distribution of x given a specific value of g. If we assume that the noise is zero-mean Gaussian with a variance of σ_n and the signal can be modelled using a Laplacian probability density function, then the estimate $\hat{x}$ can be derived [5]:

$$\hat{x}(g) = sign(g)\cdot(|g| - T)_+\,, \tag{5}$$

where $(|g| - T)_+ = \begin{cases} 0 & if\ |g| - T < 0 \\ |g| - T & if\ |g| - T \ge 0 \end{cases}$, $T = \dfrac{\sqrt{2}\sigma_n^2}{\sigma}$

The equation (5) describes the method of removing part of a signal by smoothing it. It also moves it toward zero.

The simpler method of changing some values of a signal to zero can be presented as an equation:

$$\hat{x}(g) = \begin{cases} 0 & if\ |g| - T < 0 \\ g & if\ |g| - T \geq 0 \end{cases}, \tag{6}$$

The equations (5) and (6) present two standard thresholding techniques: soft thresholding ('shrink or kill') and hard thresholding ('keep or kill'). In both cases, the values below a certain threshold are set to zero. In soft thresholding, the remaining values are reduced by an amount equal to the value of the threshold. In hard thresholding, the magnitudes of the wavelet coefficients above the threshold are left unchanged.

Figure 4 presents the results of application of soft and hard thresholding in image denoising. Hard thresholding with a small threshold does not change the image. If the threshold value is comparable with the signal, some of the values are changed to zero. Repetitions of the method do not change the image. The application of soft thresholding causes signal shrinkage even if a small threshold value is used. An image becomes darker and darker as the iterations are performed.

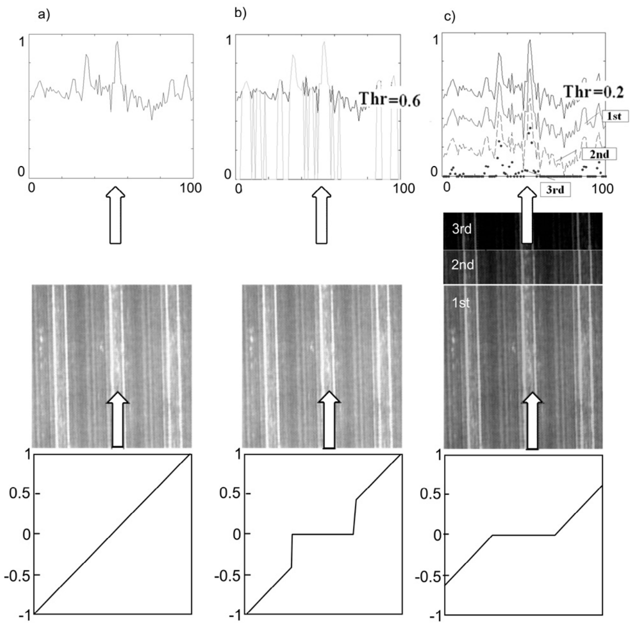

Fig. 4. a) Measured image, b) application of hard thresholding, c) application of soft thresholding

Rys. 4. a) Obraz zaobserwowany (zmierzony), b) obraz po zastosowaniu progowania twardego, c) obraz po zastosowaniu progowania miękkiego

Applying the thresholding procedure directly to the image data changes it drastically, because the noise and the signal are connected. The only solution for proper use of noise thresholding is to separate the measured signal from noise. Such a procedure is difficult to perform directly on the image, but it is quite easy to be applied when image data are presented on different scales. The Discrete Wavelet Transform of an image is a tool which distributes each scale component independently in space [5-13].

3. Image processing in wavelet domain

The Discrete Wavelet Transform (DWT) is computed separately for different segments of the space-domain image at different scales [7-8]. It analyses the image at different scales giving different resolutions. Wavelet decomposition is composed of an approximation component at low scale and wavelet decompositions at various scales. Three steps are necessary in order to use DWT in image enhancement and denoising:

1. Decomposing the image into wavelet domain.
2. Altering the wavelet coefficients, according to the applications: denoising, edge enhancement, etc.
3. Reconstructing the image with the altered wavelet coefficients.

Decomposition of the image with a certain wavelet function allows the separation of components. The better the wavelet matches the original signal, the less significant wavelet components are obtained [9-11]. If we assume that the first level DWT decomposes an image into the approximation and the details (vertical, horizontal and diagonal) are residues of the approximation model, then

1. choice of wavelets (signal modelling) affects the details in such a way that the better the model, the closer the details are to the noise,
2. since the details are residues from the model with characteristics similar to noise, the part corresponding to the noise can be removed.

This approach allows us to view the wavelet decomposition technique as the detection of data redundancy, or otherwise as a technique for defining the proper resolution in which the signal should be stored. Since the details can be treated as noise, it is recommended for them to be filtered out. In the wavelet transform domain the problem of denoising a signal can be formulated as

$$y = w + n\ , \tag{7}$$

where y is the noisy wavelet coefficient, w is the noise-free coefficient and n is noise, which is zero-mean Gaussian.

4. Results and discussion

Elimination of noise can be performed using soft or hard thresholding. Selection of the proper way to perform thresholding affects the image processing quality [12-13]. The question is how to select the wavelet components for thresholding and contrast enhancement.

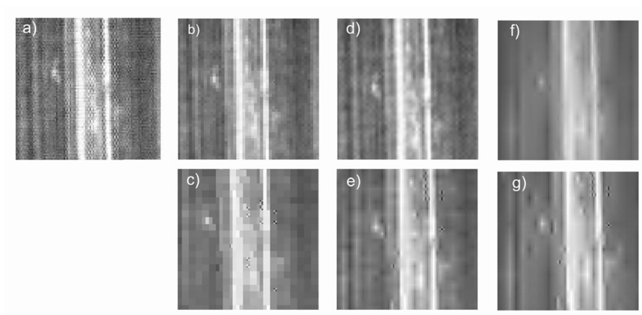

Fig. 5. Application of wavelet denoising: a) measured image, b) Haar, 2nd level, soft thresholding, UIQ=0.87, c) Haar, 2nd level, hard thresholding, UIQ=0.90, d) Coiflets 1, 2nd level, soft thresholding, UIQ=0.88, e) Coiflets 1, 2nd level, hard thresholding, UIQ=0.91, f) Coiflets 1, 6th level, soft thresholding, UIQ=0.83, g) Coiflets 1, 6th level, hard thresholding,, UIQ=0.90

Rys. 5. Zastosowanie progowania składowych dekompozycji falkowej a) obraz zmierzony, b) Haar, poziom drugi, progowanie miękkie, UIQ=0.87, c) Haar, poziom drugi, progowanie twarde, UIQ=0.90, d) Coiflets 1, poziom drugi, progowanie miękkie, UIQ=0.88, e) Coiflets 1, poziom drugi, progowanie twarde, UIQ=0.91, f) Coiflets 1, poziom szósty, progowanie miękkie, UIQ=0.83, g) Coiflets 1, poziom szósty, progowanie twarde, UIQ=0.90

Figure 5 presents the soft and hard thresholding used for denoising of machined surface images in the wavelet domain. In the case of the soft thresholding some high-frequency information is lost. This reduced the accuracy of the reconstructed signal and blurred the edges. Soft thresholding deleted the coefficients under the threshold, and the edges became thicker or not sharp.

In hard thresholding, ringing artefact was more predominant than blur. Ringing generated oscillations around the edges. This effect can be easily observed in Figs. 6c, 6e, 6g. Careful selection of the wavelet basis, thresholding procedure and threshold value is a key factor in each application of thresholding methods in the wavelet domain.

When the image is changed in some way, the change is visible as a change in the similarity measure. The UIQ measure was applied in the analysis of loss of image quality at different levels of decomposition (Fig. 7).

Approximations at the 1st and 2nd levels contain nearly complete information about the measured signal. Loss of quality is 1% for the 1st level and 4% for the 2nd level. For the next level the quality loss is more significant and deletion is not possible without significant loss of image quality. The reconstructed approximation at the 6th level has an UIQ of only 0.22, which disappears completely after several subsequent decompositions.

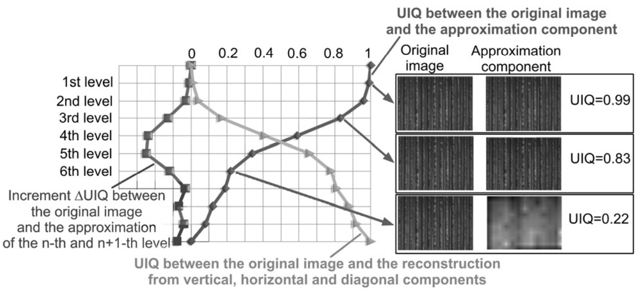

Fig. 6. Analysis of loss of image quality at different levels of decomposition
Rys. 6. Analiza utraty jakości obrazu na poszczególnych poziomach dekompozycji

Analysis of the results shown in Fig. 6 helps to examine the information contained in the image in detail (Fig. 7):

- The horizontal, vertical and diagonal components of the 1st and 2nd levels of decomposition contain mainly noise – for these components the denoising process can be applied,
- The horizontal, vertical and diagonal components of the 3rd, 4th and 5th levels of decomposition represent the most valuable part of the measured image – these components can be kept unchanged or the deblurring process can be applied,
- The approximation component at the 6th level describes the measured image to a degree of only 22% in terms of UIQ – this component does not represent the identity of the measured image, but the background to the information. It can be kept unchanged or equalization of the light disturbance can be applied.

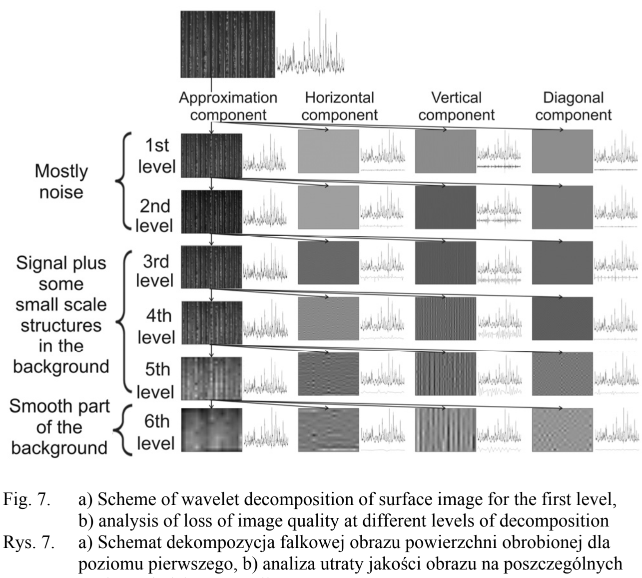

Fig. 7. a) Scheme of wavelet decomposition of surface image for the first level, b) analysis of loss of image quality at different levels of decomposition
Rys. 7. a) Schemat dekompozycja falkowej obrazu powierzchni obrobionej dla poziomu pierwszego, b) analiza utraty jakości obrazu na poszczególnych poziomach dekompozycji

Based on the above considerations, a procedure of surface image processing was developed. The wavelet decomposition was performed and the UIQ index was calculated. Based on its value, the decision concerning the image processing was made. First, the level at which the signal drastically reduced the information content was determined. This was the highest level of decomposition. The components of this level were subjected to equalization, leaving the signal energy at the same level. Changes in the image signal caused a minor change in quality. The quality index UIQ decreased by 0.004.

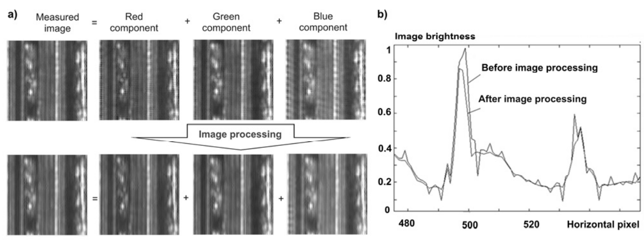

Fig. 8. a) Fragment of the surface image before and after image processing, b) a single line of the image part – original and processed
Rys. 8. a) Pierwotny fragment obrazu powierzchni obrobionej oraz ten sam fragment po przekształceniach, b) pojedynczy wiersz fragmentu obrazu pierwotnego i przefiltrowanego

Then the horizontal, vertical and diagonal components from the first to the second-last level of decomposition were checked as to whether they contained mainly noise. Their structural content was investigated using the UIQ measure. If the component was uncorrelated with the measured image, then the component was soft-thresholded. A level higher than the threshold was labelled as valuable and was deblurred using Gaussian PSF with parameters based on the energy from the thresholded components.

An example of the application of the wavelet decomposition in image processing is presented in Fig. 8. The final UIQ measure between the measured and enhanced image is 0.95. This value is the result of three image-processing procedures resulting in changes in the image, and it is significant. Given that UIQ is a multiplier for three quantities, it was found that the loss of correlation had the greatest effect on its value. This originates from the fact that changes were made in light compensation. Removal of noise and enhancement of ‘edges’ had the least influence on the image, preserving the information content of the image.

5. Conclusions

An image of surface finish can be used to assess the state of the surface. However, this requires a standardization procedure. This paper proposes a procedure for image processing, consisting of a set of techniques that are performed together to enhance its quality. The image processing procedure consists of three blocks of transformations performed on the components of selected levels of a two-dimensional Discrete Wavelet Transform.

The method of wavelet selection means that some components of wavelet decomposition meet the Gaussian white noise assumption. These components were soft-thresholded. The energy loss from the thresholding operations was compensated by strengthening the first unfiltered component. A deconvolution procedure was applied for this purpose. The wavelet decomposition divides the measured image into a number of components. The term “top-level” denotes the level of decomposition at which the reconstructed image approximation is similar to the original image in the sense of UIQ. At this level, compensation of surface lighting uniformity is performed.

Each time, the overall image processing leads to a decrease in the original universal image quality index UIQ. The change is not greater than 5% with image energy preservation.

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