Image reconstruction using the bispectrum and tapering pre-distortions of image rows

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The problem of jittery and noisy image reconstruction is considered. Bispectrum-based image row Fourier magnitude and phase spectra reconstruction technique and algorithm using pre-distortions of image rows are designed and investigated. Tapering pre-distortion function of Gaussian shape introduced in each image row permits to decrease spectral leakage, obtain continuous image row phase bispectrum functions, avoid phase ambiguity and align the reconstructed image rows. Proposed approach provides image enhancement for applications to a priori unknown object recognition. Computer simulations are provided to demonstrate the performance of the proposed image reconstruction technique. Visual inspection of the reconstructed test images illustrates heavy jitter removal and spectral leakage decreasing in the presence of additive white Gaussian noise (AWGN).

1. INTRODUCTION

Signal processing techniques and algorithms based on bispectrum estimation have found wide applications for filtering problems, signal reconstruction of unknown waveform, object classification and recognition in astronomy [1], biomedical engineering [2], radars [3], sonars [4], and others. Due to the following appealing properties of bispectrum-based analysis such as preservation of signal phase and magnitude Fourier spectra; non-sensitivity of signal recovered from bispectrum to temporal or spatial shifts of original signal (translation-invariance property); suppression of AWGN of unknown variance (carried out under condition of the large number of observations participated in ensemble averaging) and extraction of non-Gaussian signal information in Gaussian noise environment, the use of bispectrum for 1-D signal processing has become a subject of great interest [5].

It is well known that the information about the signal shape resides primarily in the signal phase Fourier spectrum and not in the magnitude Fourier spectrum or power spectrum. Indeed, several different signal shapes may have similar power spectra. Since bispectrum preserves signal Fourier phase, it is natural to expect promising results in cases of bispectrum-based 2-D image reconstruction.

Recently, several bispectrum-based image reconstruction algorithms has appeared in the literature [6 – 9]. Nevertheless, the existing bispectrum-based approaches have the following restrictions: (i) since bispectrum is translation invariant, image row Fourier spectrum recovered from bispectrum corresponds to a circularly shifted row that might cause image distortions and result in problem of image row alignment; (ii) signal phase Fourier spectrum recovery from bispectrum argument provides accurate results only when bispectrum phase values are within the phase principal value interval $[-\pi, +\pi]$, otherwise phase discontinuities at $-\pi$ and $+\pi$, phase ambiguity and image reconstruction errors arise; (iii) phase unwrapping used to overcome phase ambiguity can lead to phase errors in the presence of heavy AWGN.

Image reconstruction technique [10] allows to overcome aforementioned phase bispectrum discontinuities by introducing in each image row ends the additive pre-distortions in the form of large amplitude δ–impulses. However, this technique resulted in arising significant errors that are mainly concentrated at the leftmost and rightmost pixels of each reconstructed image row [10]. These errors appeared due to difficulties of additive pre-distortion compensation at the final stage of data reconstruction as well as due to spectral leakage. Moreover, bispectrum estimates (BEs) obtained for multiple noisy image realizations (image frames) have been employed in our previous paper [10] to suppress AWGN.

In this paper we propose to use multiplicative tapering pre-distortions of the image rows that allows jitter removal, spectral leakage decreasing, and phase ambiguity avoidance.

This paper is organized as follows. In Section 2, image reconstruction problem in jittery and noisy environment is formulated. In Section 3, we consider the proposed unknown object image reconstruction algorithm using bispectrum-based recovery of pre-distorted image row Fourier magnitude and phase spectra. In Section 4, we describe computer simulation conditions and analyze experimental results, and Section 5 concludes the paper.

2. PROBLEM STATEMENT

In practice of image reconstruction and object recognition there are a number of situations where the observation images are the sequence of noisy and jittery frames of a priory unknown object. Due to random misalignment of the image rows from frame to frame (jitter), a simple ensemble averaging can not be employed in this case to improve signal-to-noise ratio (SNR) and object recognition. Some examples using bispectrum-based approaches as a way to unknown object shape reconstruction in such jittery and noisy environment are described in [6, 7]. The main idea of these approaches is based on the translation-invariance property of the bispectrum. In this paper we are focusing on development of bispectrum-based approach for the important practical cases where each image frame is corrupted by random misalignment of adjacent image rows and AWGN.

Let us consider a 2-D digital image of a priori unknown object received in a visual communication system. Suppose this image is corrupted by zero-mean AWGN (pixel distortions) and relative positions of image rows are randomly circularly shifted with respect to their true locations due to jitter influence (spatial distortions). We also assume that each k-th (k=1,2,3,…,I) image row is a real valued sequence $\{x_k^{(m)}(i)\}$ (i=1,2,3,…,I) that is observed at the digital reconstruction system input as the following m-th (m=1,2,3,…,M and $M \neq 1$ in general case) realization (m-th repeating frame)

$$x_k^{(m)}(i) = s_k(i - \tau_k^{(m)}) + n_k^{(m)}(i), \qquad (1)$$

where $\tau_k^{(m)}$ denotes *a priori* unknown random spatial shifts of the original real valued deterministic mixed phase discrete signal $s_k(i)$ (i.e., original a priori unknown shape of the k-th image row), that we want to reconstruct for object recognition; $n_k^{(m)}(i)$ is the m-th realization of AWGN with unknown variance. We also assume that $\{\tau_k^{(m)}\}$ are independent and identical distributed random integers that values are considerably less than I.

In practice relative random displacement between adjacent image rows (jitter) can be provoked by stochastic properties of telecommunication noisy channel, mechanical raster scanning system errors as well as by data digitizing from a noisy analog image. In the latter case, synchronization pulses are corrupted by AWGN affecting the loss of “lock” in digitizing device [11]. One can say that heavy jitter is one of the essential restrictions in high speed video telecommunication systems.

Notice that the considered original image and interference model (1) is more complicated than the conventional ones described in [6, 7]. In these papers, to simulate spatial and pixel distortions the total sequence of 16256 samples (original image was of size 127x128 pixels) has been randomly placed repeatedly in a 1-D noisy frame of 16384 samples. However, an important aspect of the problem of adjacent rows de-jittering was not treated yet. Furthermore, images restored by approach stated in [6, 7] are circularly shifted and these images need manual realignment that is a quite time consuming process. Note, that this is practically inappropriate for automatic pattern recognition systems.

To alleviate these shortcomings and restrictions, the novel approach to enhancement of image reconstruction performance in adjacent image rows jitter and AWGN environment is proposed below.

3. PROPOSED TECHNIQUE FOR IMAGE RECONSTRUCTION

The proposed unknown object shape reconstruction technique includes the following processing stages and steps.

Stage 1. De-jittering of adjacent image rows.

Step 1.1. Estimation of the sampled cross-correlation function $\hat{R}_{k,k+1}^{(m)}(l)$ calculated for each two adjacent jittery and noisy image rows (1) according to

$$\hat{R}_{k,k+1}^{(m)}(l) = \sum_{i=1}^{I} x_k^{(m)}(i) x_{k+1}^{(m)}(i-l), \qquad (2)$$

where l=1,2,3,…,I is the spatial delay index.

Step 1.2. Evaluation and storage the maximum coordinates $\{l_{\max k'}^{(m)}\}_{jit}$ of the functions (2) as

$$\{\hat{R}_{k,k+1}^{(m)}(l)\}_{\max} \Rightarrow \{l_{\max\, k'}^{(m)}\}_{jit}, \qquad (3)$$

where k'=1,2,3,…,I-1.

Notice that the total number of the cross-correlation functions (2) is equal to I-1.

Step 1.3. Computations of the jitter corrections $\Delta_k^{(m)}$ by

$$\Delta_k^{(m)} = \{l_{\max k'}^{(m)}\}_{jit} - l_{center}, \quad (4)$$

where l_{center} is the row center coordinate that suppose to be corresponding to the coordinates of the maximums of original adjacent row cross-correlation functions. This peculiarity of the image row cross-correlation function is described in the paper [12].

Step 1.4. Jittery rows alignment by their shifts according to the corrections (4) . After de-jittering, the expression (1) can be rewritten in the form

$$x_{k\,cor}^{(m)}(i) \cong s_k(i) + n_k^{(m)}(i). \qquad (5)$$

Stage 2. Spectral leakage decrease and Fourier phase spectrum discontinuity avoidance.

Step 2.1. Multiplication of the de-jittered functions (5) by some pre-distortion function that Fourier spectrum pronouncedly has no zeros and, hence, the total function magnitude Fourier spectrum does not contain zeros. As such pre-distortion, tapering Gaussian shape function has been chosen in the simplest case. Pre-distorted image row then can be expressed as

$$f_k^{(m)}(i) = w_{pr}(i) x_{k\,cor}^{(m)}(i),\ i \in [1,L] \qquad (6)$$

$$f_k^{(m)}(I-i+1) = w_{pr}(i) x_{k\,cor}^{(m)}(I-i+1),$$

where $w_{pr}(i)$ is the pre-distortion tapering function defined by

$$w_{pr}(i) = e^{[\mu(L-i)]^2}, \qquad (7)$$

where variables $L<I/2$ and μ determine spread and slope of the function (7), respectively.

It should be noted, that signals (6) will be of maximum phase signals if maximum of the pre-distortion function (7) satisfies to the following condition

$$\{w_{pr}(i)\}_{\max} >> \sum_{i=1}^{I} x_k^{(m)}(i),\ k=1,2,3,\ldots,I. \qquad (8)$$

Step 2.2. Computation of the sampled m-th BEs according to

$$\hat{B}_{f_k}^{(m)}(p,q) = \left[X_{k\,cor}^{(m)}(p) \otimes W_{pr}(p)\right] \left[X_{k\,cor}^{(m)}(q) \otimes W_{pr}(q)\right] \left[X_{k\,cor}^{(m)*}(p+q) \otimes W_{pr}^{*}(p+q)\right], \qquad (9)$$

where $X_{k\,cor}^{(m)}(...)$ and $W_{pr}(...)$ are the direct discrete Fourier transforms of the functions (5) and (7), respectively; ⊗ and * denote the convolution and complex conjugation, respectively; p=1,2,3,…,I and q=1,2,3,…,I are the independent spatial frequency indices.

It should be noted that the role of the tapering pre-distortion (7) is threefold:

- to obtain improved BE (9) due to spectral leakage decrease in the sense of BE bias decrease;

- to eliminate bispectrum phase wrapping due to transform of image rows to the maximum-phase signals;
- to fix the coordinate of each k-th image row center of gravity (CG_k) and, hence, to automatic image rows alignment after bicpectrum image row reconstruction.

Stage 3. Bispectrum-based image row reconstruction.

Step 3.1. Image row phase and magnitude Fourier spectra recovery from the BEs (9) by conventional recursive algorithm [1].

Step 3.2. Image row reconstruction by discrete inverse Fourier transform of the image row Fourier spectrum recovered from BE.

Step 3.3. Compensation of the pre-distortions (7) by multiplying of the reconstructed image rows by the function inverse to (7).

4. SIMULATION RESULTS

In this paper we consider the reconstruction of the 8-bit test images with sizes of IxI=256x256 pixels. In Figures 1 and 2 the noise- and jitter-free test images are shown. Pixel intensity close to 256 are painted white, whereas pixel values close to 0 are painted black.

AWGN with zero mean and with fixed variance of 100 was added independently to each image row. Random image row shifts $\tau_k^{(m)}$ (see expression (1)) have been simulated with fixed maximum deviation of ±15 pixels. The first test object ("Barbara") and the second one ("Letters") corrupted by AWGN and jitter are shown in Fig.3 and Fig.4, respectively. As can be seen from Fig.3 and Fig.4, the images are completely concealed by jitter and AWGN and it is impossible to recognize visually an a priori unknown object (to percept this image).

Sampled cross-correlation function estimates derived between adjacent jittery and noisy row images in Fig. 4 and calculated according (2) are shown in Fig. 5. It is clearly seen from Fig. 5, that cross-correlation function estimate maximums are randomly jagged due to the heavy jitter influence (white color corresponds to maximum).

Image row phase Fourier spectra of the original image, the noisy and jittery pre-distorted one, and sampled row phase BE (M=1) are shown in Figures 6, 7 and 8, respectively. Notice that the curves illustrated in Figures 6, 7 and 8 are given for phase values plotted in the vertical axes and bounded by [-π, π]. Pre-distorted image row phase Fourier spectrum shown in Fig.7 has not any discontinuity (wrapping) as opposed to the original image row phase Fourier spectrum (see Fig.6) wrapped to the principal phase range [-π, +π].

One can see, that there is no phase wrapping in the pre-distorted row phase BE (see Fig. 8). Hence, phase errors in the reconstructed image row caused by phase aliasing and ambiguity can be pronouncedly decreased.

To thoroughly study the performance of the developed technique, the original and corresponding reconstructed image rows are represented in Figures 9 and 10. As seen, the proposed technique provides reasonable reconstructed image row quality in the sense of AWGN suppression in quite heavy jitter and AWGN environment even with only one (M=1) available realization.

Figures 11 and 12 illustrate the images reconstructed by the proposed technique for L=32 pixels and μ=0.065 that corresponds to $\{w_{pr}(i)\}_{\max}$=14787 (see condition (8)). As can be seen, the reconstructed images are sufficiently cleaner than the distorted ones in Figures 3 and 4.

The reconstructed objects illustrated in Figures 11 and 12 can be confidently recognized despite the slightly jagged vertical image edges.

Unfortunately, there are the distortions in the reconstructed images in the form of little circular shifts of some image rows. These distortions are caused due to the centering of the bispectrum reconstructed k-th image row with respect to the CG_k coordinate. If original image row was $s_k(i)$, then the reconstructed image row $\hat{s}_k(i)$ will be centered with respect to CG_k coordinate and

$\hat{s}_k(i) = s_k(i - CG_k)$. Hence, despite satisfaction of the condition (8) as a whole, the CG_k coordinates of some pre-distorted image rows may be slightly shifted (jagged) relatively the central image row pixel. The residual jags of CG_k coordinate can be explained by large gradient of intensities in different image rows.

5. DISCUSSION AND CONCLUSIONS

Bispectrum-based approach that is promising for reconstruction and enhancement of a priori unknown object images corrupted by AWGN and adjacent image row jitter has been proposed and investigated by computer simulations. Our approach is based on jitter removal and automatic reconstructed image alignment by pre-distorting of the processed image rows. Due to introduction of the tapering multiplicative pre-distortions, only the principal arguments of the phase bispectrum are obtained. As a result, bispectrum phase aliasing and wrapping are pronouncedly decreased. Therefore, phase unwrapping procedure is avoided and phase errors are decreased in reconstructed images.

Computer simulation results demonstrate the procedure reasonable robustness to AWGN and jitter in the case of only one image realization observed (M=1 in the formula (1)). Further reconstructed image quality improvement can be expected if more observed realizations (M>1) are available. Another pre-distortion functions can be employed to improve BEs and, hence, to make better the image reconstruction system performance.

The proposed technique and the developed algorithm can be useful for practical applications in automatic object recognition systems that operate under a priori unknown object and interference characteristics in heavy jitter and additive noise environment.

6. REFERENCES

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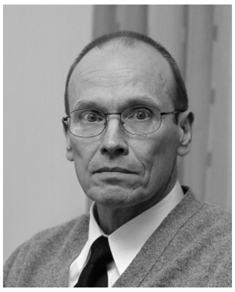

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Figure 1. The original noise- and jitter-free test image (“Barbara”).

Figure 2. The original noise- and jitter-free test image (“Letters”).

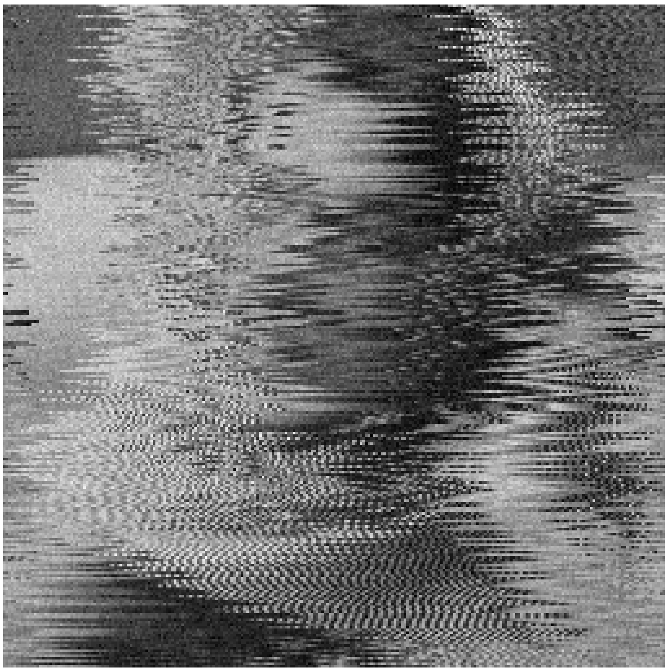

Figure 3. Object “Barbara” corrupted by AWGN and jitter.

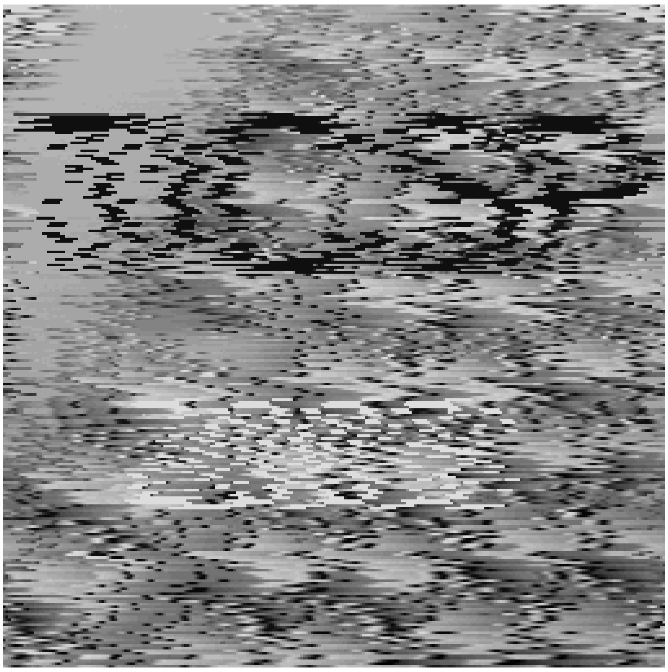

Figure 4. Object “Letters” corrupted by AWGN and jitter.

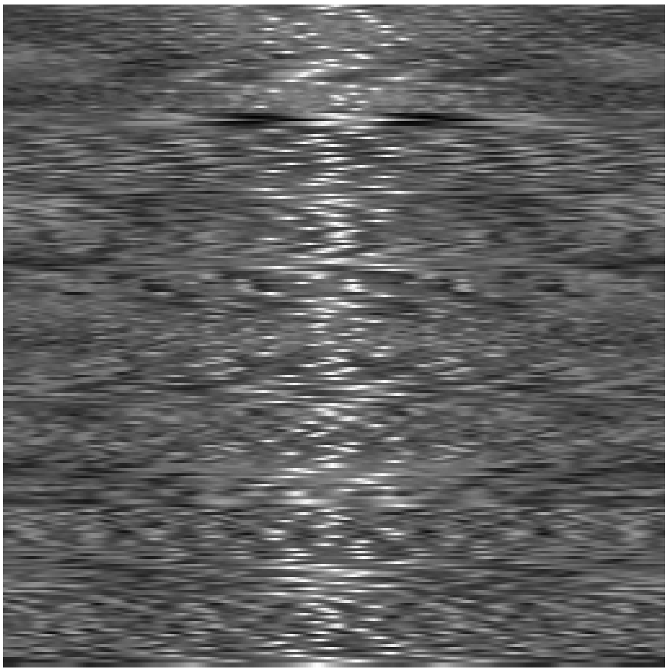

Figure 5. Cross-correlation function estimates (2) derived between adjacent jittery and noisy image rows in Fig. 4.

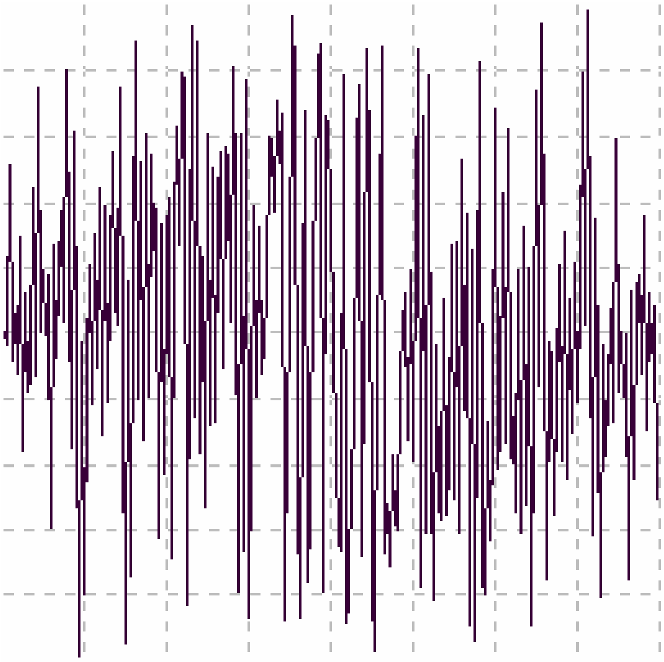

Figure 6. Phase Fourier spectrum of a noise- and jitter- free original image row in Fig.2.

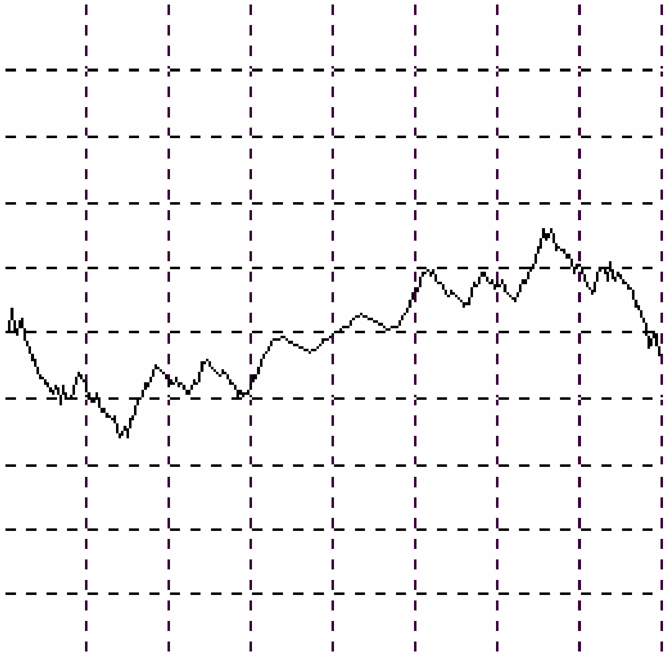

Figure 7. Phase Fourier spectrum of the corresponding pre-distorted image row in Fig.4.

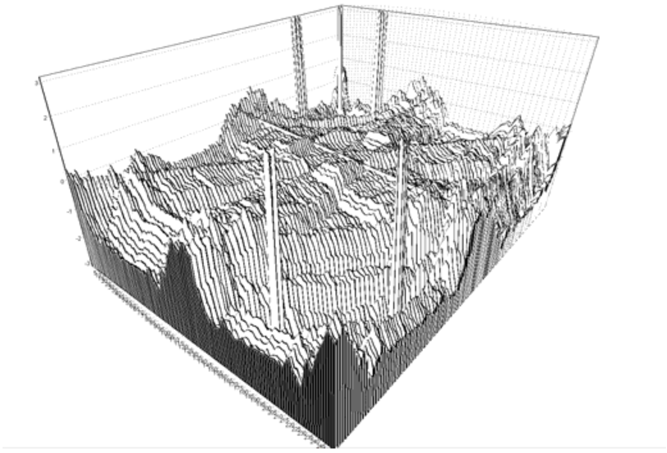

Figure 8. Phase bispectrum estimate (M=1) of the pre-distorted image row in Fig.4.

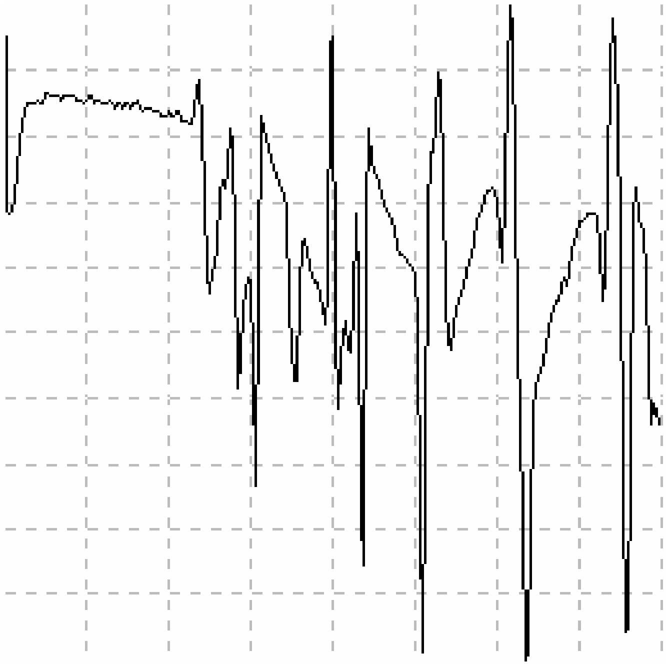

Figure 9. A noise- and jitter-free original image row in Fig. 2.

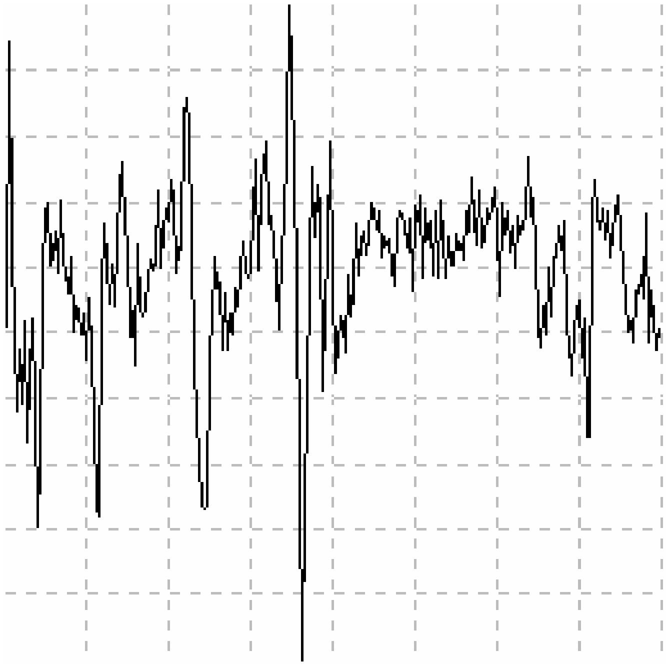

Figure 10. Image row reconstructed from the image in Fig. 4.

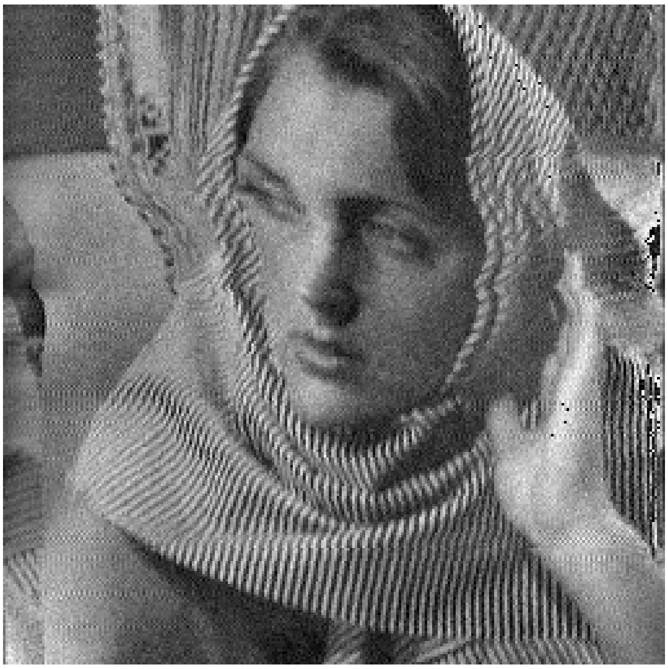

Figure 11. Reconstructed object “Barbara”.

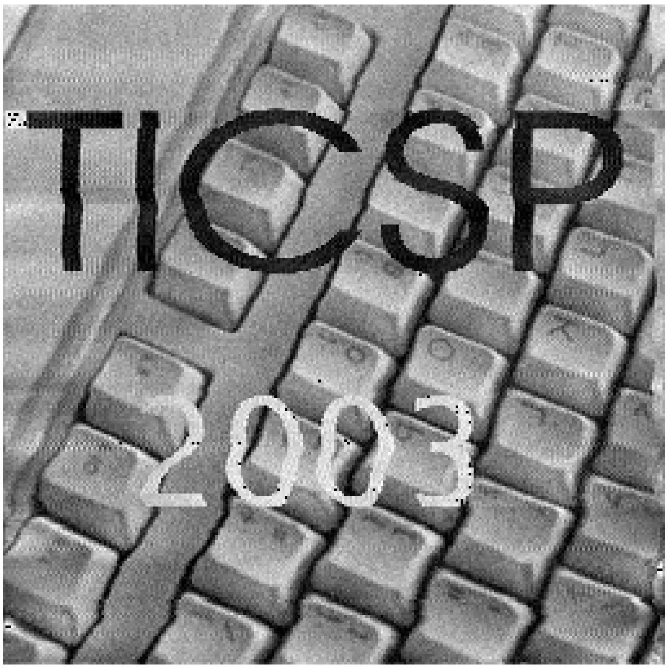

Figure 12. Reconstructed object “Letters”.