The technology of forming adaptive recovery filters in mobile devices

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Abstract. This paper deals with the technology of forming adaptive filters to eliminate distortions such as defocus on images recorded using mobile devices. The main purpose of the development is to ensure a sufficiently high quality of the distortion correction with minimal computational costs. The blind parametric identification of the model with a radially symmetric quadratic-exponential frequency response is used to adjust the filter parameters. The algorithm, the pseudo-code of the program and the results of experiments demonstrating the effectiveness of the proposed approach are given.

1. Introduction

In recent years, there has been an increasing interest in the problem of processing images recorded by mobile devices. This is due to the possibility of real-time registration of natural subjects and scenes at relatively low costs. However, these images are often subject to distortion, which manifests itself in the form of blur. This may be due to the small depth of field of the lens. In addition, the blurring of images often occurs due to the fact that shooting is performed “from the hands”, as well as when a recorded object moves at high speed.

Recently, in a number of papers, the idea of image registration by devices built using diffractive optical elements (DOEs) has also been actively discussed. [1], [2]. In this case, hopes are associated with the improvement of the technology for creating DOEs, in particular, with the creation of lenses based on the Fresnel imaging lens. [3], [4]. Unfortunately, the quality of images generated using DOEs is still noticeably lower than images of the traditional optical systems. Perhaps the creation of compact mobile applications of digital image processing, which to some extent can compensate for this shortcoming, would give a new impetus to the construction of mobile devices based on DOE.

These circumstances served as the motive for conducting research, the results of which are given in this paper. We set the task of developing a technology that would provide a relatively high quality of the distortion correction with minimal computational costs, allowing the implementation of the technology in mobile devices. Based on this goal, in the present work we build the technology of forming adaptive recovery filters in the class of filters that are a generalization of the quadratic-exponential (SE-filter) considered in the paper [5].
2. Problem statement

We will construct a FIR filter with a radially symmetric real frequency response [5], represented as a surface formed by the rotation of the one-dimensional frequency response around the point of origin. The function of one-dimensional frequency response for all values $0 \leq \omega < \infty$ is given in the form of three consecutive segments: parabola, constant and exponential function:

$$S(\omega) = \begin{cases} \alpha \omega^2, & \text{при } 0 \leq \omega < \omega_1, \\ A = \text{const} = \alpha \omega_1^2, & \text{при } \omega_1 \leq \omega \leq \omega_2, \\ e^{-i\omega}, & \text{при } \omega \geq \omega_2, \end{cases}$$

(1)

The filter corresponding to the described frequency response, is called as a quadratically exponential filter (Square-Exponential) or briefly a GSE-filter.

The impulse response corresponding to this spectral characteristic, by virtue of the radial symmetry property, is obtained as a function of the spatial parameter $r$, using the inverse Fourier transform:

$$
\begin{align*}
    h(r) &= \frac{1}{\pi} \int_0^\infty S(\omega) e^{i\omega r} d\omega = \frac{1}{\pi} \left\{ \left[ \alpha \omega^2 e^{i\omega r} d\omega + \left[ e^{-i\omega} d\omega \right] \right] + A e^{i\omega r} d\omega \right\} \\
    &= e^{-i\alpha r} \left( \frac{\sin \omega_1 r}{r \sin \omega_1 r} + \frac{2 \cos \omega r - 2 \sin \omega r}{\omega r} \right) + \left( \frac{\cos \alpha \omega r - r \sin \omega r}{c^2 + r^2} \right) \\
    h(0) &= \lim_{r \to 0} h(r) = \frac{\alpha \omega c (3 \alpha - 2) + 3}{3 c \pi} \ e^{-i\alpha r} \ (3)
\end{align*}
$$

(2)

(3)

(we excluded $\alpha$ and $\omega_2$, taking into account (1) substitution $\alpha = \frac{e^{-i\alpha r}}{\omega_1^2}$, and take $\omega_2 = \omega_1$).

In the spatial domain, we define the reference window $D$ in the form $N \times N$ of a square centred at a point $k_1 = 0$, $k_2 = 0$. Assuming that the central sample of the impulse response $h(0)$ of the reference window $D$ is at a point $n_1$, $n_2$, counts of the reconstructed image $y(n_1, n_2)$ can be represented as:

$$y(n_1, n_2) = \sum_{k_1=-\frac{N-1}{2}}^{\frac{N-1}{2}} \sum_{k_2=-\frac{N-1}{2}}^{\frac{N-1}{2}} h(r(k_1, k_2)) \delta(n_1 - k_1, n_2 - k_2)$$

(4)

where $r(k_1, k_2) = \sqrt{k_1^2 + k_2^2}$, $a_h[r(k_1, k_2)]$ - one-dimensional impulse response counts defined on a set of circles with radii $r = r(k_1, k_2), k_1, k_2 \in D$.

The counts of the two-dimensional impulse response are determined by discretizing the continuous function (2) for all directions corresponding to all the counts of the reference area.[5]. In addition, for each count (points $k_1, k_2$) in the relation (2) the argument is $r = r(k_1, k_2) = \sqrt{k_1^2 + k_2^2}$ . Then, all the counts in the reference area are normalized so that the requirement to maintain the average brightness level of the processed image is fulfilled: $\sum h(k_1, k_2) = 1, \forall k_1, k_2 \in D$ (5).

In the paper [5], the traditional technology of component-wise processing of colour RGB images within the framework of the described SE-filter model was implemented. In this paper, using the same filter model, we will construct a technology that reduces the amount of computation. All experiments are carried out on images registered with a diffraction lens built on the basis of a Fresnel lens.

3. Image processing technology with filter settings

Using the quadratic-exponential frequency response model described above, we will construct several technology options that take into account the specific features of image distortions generated by DOE. It is known that a rather strong dependence of the refractive index on the wavelength is characteristic
of the imaging Fresnel lens. As a result, there are significant differences in focal lengths for different colour components. Therefore, depending on the distance from the lens to the recording matrix, the colour components may have significantly different degrees of blurring. With this in mind, we will build a basic technology for component-based processing of RGB images, in which the parameters of the recovery filter model in different colour channels are determined independently and can vary greatly. Component processing of RGB images is implemented using the following algorithm.

Algorithm 1.
1. Selection of one component (R, G or B) from the processed image.
2. Setting initial estimates of parameters \( \hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x \) and criteria \( Q(\hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x)(n = 0) \) for a monochrome image of the selected component.
3. Calculation of impulse response counts for all points of the reference area \( D(n_1, n_2) \) using relations (2), (3) and normalization of all counts satisfying (5).
4. Processing of the distorted monochrome image in accordance with (4).
5. Calculation and verification of the criterion for improving the quality of the processed image: if
   \[
   PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_N)) > PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_{N+1}))
   \]
   (6), under conditions
   \[
   D(\hat{X}_x) > D(\hat{X}_{x-1}), \quad PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_N)) > PSNR_{\min, \hat{X}_x} \quad D(\hat{X}_x) > D(\hat{X}_{x-1}),
   \]
   estimates \( \hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x \) are saved. If not all estimates from the range of acceptable values are “viewed” - a new version of the estimates is formed and the conversion to step 3 is carried out.
6. If not all components (R, G and B) are processed, the selection from the processed image of the next component and the conversion to step 2, otherwise the output.
7. Build a full colour RGB image.

Along with the described base technology, we would also consider the image processing technology in the LAB colour space. It is known that in this colour space the \( L \) component contains information about the distortion of the type of defocus; therefore, to eliminate the distortion is enough to process only one component. In this regard, it is interesting to find out whether it is possible to reduce the volume of calculations in this case? The processing algorithm with the settings of filter parameters in the LAB colour space has the form:

Algorithm 2:
1. The conversion from RGB colour model to LAB.
2. Setting of the initial estimates of the parameters \( \hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x \) and criteria \( Q(\hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x)(n = 0) \) for the monochrome image of the \( L \)-component.
3. Calculation of impulse response counts for all points of the reference area \( D(n_1, n_2) \) using relations (3), (4) and normalization of all counts that satisfies (5).
4. Processing a distorted monochrome \( L \)-component of the image in accordance with (4).
   Calculation and verification of the criterion for improving the quality of the processed image: if
   \[
   PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_N)) > PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_{N+1}))
   \]
   (6), under conditions
   \[
   D(\hat{X}_x) > D(\hat{X}_{x-1}), \quad PSNR(X, \hat{X} (\omega_{1, n}, c_n, \alpha_N)) > PSNR_{\min, \hat{X}_x} \quad D(\hat{X}_x) > D(\hat{X}_{x-1}),
   \]
   estimates \( \hat{\varphi}_x, \hat{c}_x, \hat{\alpha}_x \) are saved. If not all estimates from the range of acceptable values are “viewed” - a new version of the estimates is formed and the conversion to step 3 is carried out.
5. Conversion from LAB to RGB.

Note that in both of the above algorithms, blind identification of filter parameters is implemented (without a reference image). Using algorithms I and II, various variants of technology implementation are possible. Table 1 shows the technologies that will be investigated in this work.

The algorithms for setting filter parameters and processing one (R, G or B) RGB-image component and/or \( L \)-component in the LAB colour space are the same. Therefore, to implement any of the technologies listed in Table 1, it is sufficient to create a software function for processing one component. In addition, it is also necessary to implement a program code for switching from RGB to LAB and back.
Table 1. Image processing technologies with filter settings.

| №   | Technologies with pre-blind filter settings                                      |
|-----|-------------------------------------------------------------------------------|
| 1   | Processing one, the most "blurry" (R, G or B) component                        |
| 2   | Processing of all three (R, G and B) components with independent adjustment of filter parameters |
| 3   | L-component processing in LAB colour space without preprocessing RGB image     |
| 4   | L-component processing in LAB with preprocessing of one of the most “blurred” RGB-image component |
| 5   | L-component processing in LAB with preprocessing of all RGB image components   |

4. Implementation of a mobile application

It can be seen from Table 1 that any of the technologies indicated in this table can be implemented by different organization of three software modules: processing of one component, conversion from RGB to LAB and reverse conversion from LAB to RGB. The general scheme of the application that implements all of these technologies is presented in Figure 1.

![Figure 1](image)

Figure 1. The general scheme of the automated formation of processing technology.

Here, the control module provides adaptive automated control of the choice of processing technology. This module implements a scheduler program that establishes the sequence of connecting processing modules and conversions to colour spaces. The choice of technology number is carried out by the user.

Figure 2, a shows the pseudo-code of a software module that implements processing of one component, Figure 2, b shows the pseudo-code of a software module implementing the algorithm for switching from RGB to LAB, and Figure 2, c shows the pseudo-code of the software module of the reverse conversion from LAB to RGB.

Input: distorted image – source_image_RGB

for source_image_RGB the selection of the most distorted channel, for example, the blue channel – source_image_B

for source_image_blue_B do

Start function image_processing

for w ∈ (w_in, w_end)/c ∈ (c_in, c_end)/α ∈ (α_in, α_end) with step w/w_step/c/c_step/α do

start function1

for i ∈ (1, N) with step 1 do

for j ∈ (1, N) with step 1 do

r = \( \left( \left( \frac{i-N+1}{2} \right)^2 + \left( \frac{j-N+1}{2} \right)^2 \right) \)^\frac{1}{2}

if r > 0.5 then

\[ h(i, j) = \frac{\exp(-c\alpha_0)}{\pi} \left( \frac{\sin \omega_0 r}{r} \sin \omega_0 r + \frac{2 \cos \omega_0 r}{r^3 \omega_1} - \frac{2 \sin \omega_0 r}{r^3 \omega_0} + \frac{\sin \alpha_0 \omega_0 r - \sin \alpha_0 \omega_1}{r} + \frac{c \cos \alpha_0 \omega_0 r - r \sin \alpha_0 \omega_1}{c^2 + r^2} \right) \]

end

end

end

start function2

for i ∈ (1, N) with step 1 do

for j ∈ (1, N) with step 1 do

\[ XR(k,l) = XR(k,l) + X \left( k - \frac{N+1}{2} + i \right) \left( l - \frac{N+1}{2} + j \right) h(i, j) \]
calculate the value of the PSNR criterion:

\[ \text{PSNR} = 10 \log_{10} \left( \frac{\text{MAX}^2}{\text{MSE}} \right) \]

if calculated value of the PSNR < previous value of PSNR and processed image dispersion (XR) > distorted image dispersion (X) then

keep in mind the value of the parameters w/c/α

keep in mind the value of PSNR

end
call function1 and function2 with new parameter values w, c, α

output: processed image source_image_B.

End

for source_image_RGB add a blue channel from source_image_B

\( X = \frac{X}{X_n}, X_n = 0.950456 \)

\( Z = \frac{Z}{Z_n}, Z_n = 1.088754 \)

\( L = \begin{cases} 116 \cdot Y^{\frac{1}{2}} - 16, & \text{if } Y > 0.008856 \\ 903.3 \cdot Y, & \text{if } Y \leq 0.008856 \end{cases} \)

\( a = 500 \left( f(X) - f(Y) \right) + \delta \),

\( b = 200 \left( f(Y) - f(Z) \right) + \delta \).

\( f(t) = \begin{cases} t^\frac{1}{2}, & \text{if } t > 0.008856, \\ 7.787 \cdot t + \frac{16}{116}, & \text{if } t \leq 0.008856 \end{cases} \)

\( \delta = \begin{cases} 128, & \text{if the image is 8 - bit} \\ 0, & \text{if the float image} \end{cases} \)

end

for L-component of the source_image_Lab call function image_processing with calculated values of parameters w/c/α

\( X = \left( f_x - \frac{16}{116} \right) 3\delta^2 X_n, \text{where } f_x = f_y + \frac{a}{500} \)

\( Y = \left( f_y - \frac{16}{116} \right) 3\delta^2 Y_n, \text{where } f_y = (L + 16) \cdot 116, \)

\( Z = \left( f_z - \frac{16}{116} \right) 3\delta^2 Z_n, \text{where } f_z = f_y - \frac{b}{200} \)

source_image_RGB[R][G][B] =

= source_image_LAB[X][Y][Z].

\( \begin{bmatrix} 3.240479 & -1.537150 & -0.498535 \\ -0.969256 & 1.875992 & 0.041556 \\ 0.55648 & -0.204043 & 1.057311 \end{bmatrix} \)

end

Output: processed image – source_image_RGB

\( \text{Figure 2. Pseudo-codes of program modules: component processing - a); conversion from RGB to LAB - b); conversion from LAB to RGB - c).} \)

When developing a mobile application, the OpenCV library is used. OpenCV works under a variety of platforms — Linux, Windows, and Mac OS — written in a high-level language (C / C ++), contains algorithms for image interpretation, calibration of the camera by reference, eliminating optical distortion, determining similarity, analysing object movement and much more used parallelism and multi-core for the tasks performed.
5. Experimental results
In the experiments, the images «Bird» and «Veronika», shown in Figures 3, and 4, and respectively, were used. The images are obtained by shooting with a Fresnel lens. The first experiment consisted in a comparative study of the effectiveness of the image processing technologies listed in Table 1. In this experiment, only the «Bird» image was used, since for this image, along with the diffraction image, there is also a sample obtained using high-resolution optics, which can be used as a reference for assessing the quality of correction.

Figure 3,b shows the image «Bird», restored using technology 2, i.e. by independently adjusting the filter parameters on all three components of the RGB image. In Figure 3,c the same image «Bird», obtained as a result of the implementation of technology 2 and reconstructed using technology 5, is in the LAB colour space.

Table 2 shows the results of comparative studies of the quality and computational complexity of technologies based on the use of RGB and LAB representations. The quality of the image «Bird» was evaluated by the PSNR criterion in comparison with the reference image. The sequence numbers of technologies coincide with the numbers of technologies, descriptions of which are given in Table 1.

Table 2. Comparison of the effectiveness of technology on the image of «Bird».

| Technology                                      | Time (c) | $\hat{\alpha}_1,\gamma$ | $\hat{\alpha}_n$ | $\hat{\alpha}_s$ | PSNR   |
|------------------------------------------------|----------|--------------------------|-------------------|-------------------|--------|
| RGB with processing channels                   | 14.70    | 0.83                     | 9                 | 0.9               | 26.970 |
| (1) B-channel processing in RGB image          | 7.71     | 1.01                     | 10                | 1                 | 25.191 |
| (2) Independent adjustment of filters in R, G, B channels | 7.12 | 0.81                     | 9                 | 0.95              | 27.492 |
| (3) LAB without pretreatment                   | 24.72    | 0.85                     | 8                 | 0.95              | 27.086 |
| (4) LAB with blue component processing (B)     | 25.43    | 0.85                     | 8                 | 0.95              | 27.636 |
| (5) Independent processing of R, G, B + LAB    | 26.74    | 0.85                     | 8                 | 0.95              | 28.883 |

The first row of the table shows the results obtained using the traditional processing scheme in the RGB colour space with the formation of a common filter for all colour components. Note that when processing in the LAB colour space, the quality is slightly higher (technology 3); however, the processing time increases significantly (24.72).

The technology with independent tuning of filters on all RGB channels gives a noticeable gain in quality (PSNR = 27.492) compared to both of these processing options (RGB with a common filter and LAB without preliminary processing). The technology (4) of processing in LAB space with preliminary processing of one, the most "blurred" (in this case blue) component, allows to further improve the result (PSNR = 27.636). Finally, the best quality (PSNR = 28.883) is achieved using processing technology in the LAB color space after preprocessing in RGB space with independent filter tuning for each component. Note that in this case the processing time increases significantly.

Using these properties, it is possible to build adaptive recovery filters in a wide range of characteristics. Using the developed scheme, a user of a mobile application needs to select the appropriate technology, based on the quality requirements and available resources.
Figures 4, b and 4, c show the images obtained by processing the original «Veronica» image in RGB and LAB space, respectively, as an example of the use of the technologies studied.

This example is interesting because there is no reference for this image. The filter parameters are configured by blind identification. Therefore, for these images we cannot give an objective quality assessment by the PSNR criterion. In this case, only a visual assessment of quality is possible. Similarly, as in the previous example, processing of the RGB image allowed us to remove some distortion, but retaining a small vagueness of fine details. Processing in LAB-space "coped" with distortions on fine details and allowed transferring colours more brightly and more vividly.

6. Conclusion
The technology of restoration of the images registered by means of the representing Fresnel lens is realized. The program on the Android platform, designed for image processing in mobile devices, is developed. An example of processing test diffraction applications without the use of a standard is given. The result obtained when restoring the diffraction image «Bird» has the value of criterion PSNR = 28.88. The results may be of interest to users of tablets and smartphones.

7. References
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