# Computer Modeling of an Image of the Optical-Electronic System for Reference Mark Position Control

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**Abstract.** An impact of evaluation error of reference mark image energy center on accuracy of optical-electronic system for reference mark position control (OES RMPC) is considered. Basic problems related to computer modelling of reference mark image, wherein reference mark is a light source, and needed for OES RMPC accuracy estimation are analyzed. A general algorithm for reference mark image description taking into account its relative motion is presented. A numerical experiment of image restoration using Matlab is shown. It is demonstrated that, when information is processed by OES RMPC, image restoration algorithm by Wiener parametric filtration and Tikhonov regularization are the most effective.

**Keywords:** Computer modeling · Image blur · Position control · Reference mark· deconvolution image· Matlab



## 1 Introduction

When a railway track is built or repaired with modern high-performance track machines, definition of the actual railway track position and estimation of the result with technical means are important aspects for improvement of an operation of railway track placing in a required position [1, 2, 9]. An optical-electronic system for reference mark position control (hereinafter referred to as OES RMPC) developed at ITMO (St. Petersburg, Russia) enables to define the railway track position in the vertical plane (surfacing), vertical relative position of track rails (transverse gradient) and horizontal position (realigning) relative to reference marks conjugated to geodetic network coordinates, as the track renewal train runs. The minimal error is limited by the accuracy of reference mark image energy center definition [3, 10, 11] on the receiving senor array. This error depends on the number of parameters, such as video camera pixel size, optical system aberration characteristics, background luminance distribution and reference mark (RM) image smear. The objective of the paper is to form a computer model, which synthesizes a smeared RM image in different background luminance distributions, and to estimate the error of coordinate definition in the restored smear-free image, considering RM relative motion.

## 2 Impact of evaluation error of RM image energy center on OES RMPC accuracy

In the category of systems we are considering [12, 4, 5], to define the energy center (EC) of the RM image the weighted summation method is used, the method is expressed with formulas (1), (2) and provides an accuracy of less than 0.1–0.01 pixel [6, 7].

$$X_{EC} = \left[\sum_{i=1}^{M}\sum_{j=1}^{N}(x_{i,j} \cdot Q_{i,j})\right] \Bigg/ \left[\sum_{i=1}^{M}\sum_{j=1}^{N} Q_{i,j}\right] \tag{1}$$

$$Y_{EC} = \left[\sum_{i=1}^{M}\sum_{j=1}^{N}(y_{i,j} \cdot Q_{i,j})\right] \Bigg/ \left[\sum_{i=1}^{M}\sum_{j=1}^{N} Q_{i,j}\right] \tag{2}$$

where $X_{EC}$; $Y_{EC}$ are coordinates of the RM energy center on the sensor array, Q is a total signal from array elements.

However, the error of RM image coordinate evaluation, when the receiver is exposed to the background radiation, proper detector noise and camera motion, rises dramatically, thus increasing the total error of the system.

Attenuation of image distortion influence generally consists in using specialized optical systems or high-speed cameras, which makes implementation of the system more complex. Due to use of software it is possible to eliminate a number of optical distortions by means of mathematical processing of the images, it is possible to lessen requirements to imaging system hardware [13].

## 3 Restoration methods of the distorted image

For an effective energy center coordinates definition, the following known methods for distorted RM image restoration can be used [17, 14, 18]:

- inverse filtering

$$\widehat{F}(u,v) = F(u,v) + \frac{N(u,v)}{H(u,v)} \tag{3}$$

- optimal Wiener filtration

$$\widehat{F}(u,v) = \left(\frac{1}{H(u,v)}\frac{|H(u,v)|^2}{|H(u,v)|^2 + \frac{S_n(u,v)}{S_f(u,v)}}\right).G(u,v) \tag{4}$$

- smoothing functional method (Tikhonov method)

$$\widehat{F}(u,v) = \left(\frac{H^*(u,v)}{|H(u,v)|^2 + \gamma|P(u,v)|^2}\right).G(u,v) \tag{5}$$

- Lucy-Richardson method

$$\widehat{f}_{k+1}(x,y) = \widehat{f}_k(x,y)\left(h(-x,-y) * \frac{g(x,y)}{h(x,y) * \widehat{f}_k(x,y)}\right) \tag{6}$$

where $\widehat{F}(u,v)$ is a Fourier transform (FT) of the original RM image; $N(u,v)$ is a FT of random value of noise; $H(u,v)$ is a FT of a distorting operator; $G(u,v)$ is a FT of RM image; $S_n(u,v)$ is a noise energy spectrum n(x, y); $X_{EC}$ is an energy spectrum of the original image f(x,y); $X_{EC}$ is a FT of the Laplacian operator; $S_f(u,v)$ - is a regularization parameter; f, g, h are F, G, H function in the spatial domain, respectively.

The methods mentioned above are based on an a priory defined distortion operator $H(u,v)$, however, when real RM images are processed, an exact point spread function (PSF) is not known or known approximately as a result of image analysis by distinct fragments [15]. For RM image processing in case the PSF is unknown a range of blind deconvolution methods can be applied [19].

Restoration of distorted images with the methods considered doesn't prevent emergence of edge effects in restored images (e.g., false waves effect, Gibbs effect), which require additional solutions to eliminate them. The majority of distorted RM image reconstruction methods are not adequate to physical essence of the smear phenomenon and don't take into account motion speed and RM position up to a fraction of a pixel. In the present work we consider a mathematical modelling of the distortion function, which allows to understand the essence of distortion effect, which is necessary for estimation of RM image restoration algorithms, when image coordinates are defined.

## 4 Computer model of the reference mark image

To develop and study an image model of the RM as a light source, a mathematical model has been created, its general structure is shown in Fig. 1. To set the RM spatial position on the image with a precision up to a hundredth of a pixel, it is necessary to apply the shift property of the Fourier transform to the original object form. To do this, the original spectrum must by multiplied by the phase component with shift parameters $x_0$, $y_0$. The transfer function for RM spatial position setting can be defined as:

$$H_d\left(u,v\right) = e^{-i2\pi(ux_0+vy_0)} \tag{7}$$

Results of accuracy estimation of RM position setting obtained with weighted summation using Matlab are presented in table 1. It should be understood, that when this method is used, RM image mustn't be converted in a binary image (this procedure decreases measurement accuracy). From the results in the table above we see that accuracy of setting RM shifts using transfer function $H(u,v)$ (7) provides an error less than a hundredth of sensor array pixel. The transfer

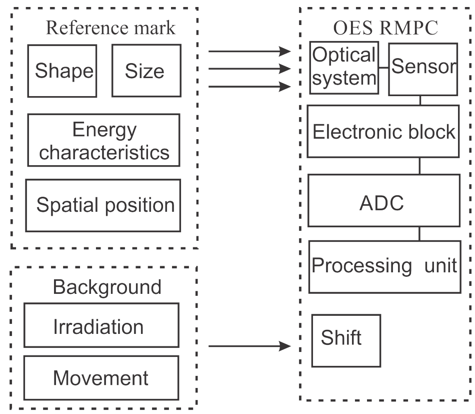



**Fig. 1.** Basic information transformations in the mathematical model of RM image formation in the OES RMPC

**Table 1.** Results of accuracy estimation of RM position setting obtained with weighted summation.

| **Actual RM image shift, px** | **Average measured shift, px** |
|---|---|
| 0.1 | 0.1094 |
| 0.01 | 0.0117 |
| 0.001 | 0.0016 |

function of the optical system, in turn, can be found through FT of function [8]:

$$H_{op}\left(u,v\right)=\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty}\frac{1}{2\pi ab}e^{-\frac{x^2}{a^2}}e^{-\frac{y^2}{b^2}}e^{-i2\pi(ux+uv)}dxdy \tag{8}$$

When RM image f(x,y) moves relative to OES RMPC according to functions $x_0(t)$ and $y_0(t)$ (along spatial axes x and y respectively), the total exposure when RM image is acquired will be defined as time integral of instant exposure T. In this case, the image smear model transfer function can be found through FT as:

$$H_l\left(u,v\right)=\frac{T}{\pi(ua+vb)}\sin\left(\pi(ua+vb)\right)e^{-i\pi(ua+vb)} \tag{9}$$

where a, b - are RM image shifts during exposure time T. Besides the functions shown above, RM image formation model also considers the following parameters: RM type, its shape and size (see Fig. 2a), background radiation distribution (see Fig. 2b), observation conditions (see Fig. 2c), properties of a detector of optical radiation.

Based on proposed elements of generalized OES RMPC imitation model a synthesis function of RM digital image is obtained [16]:

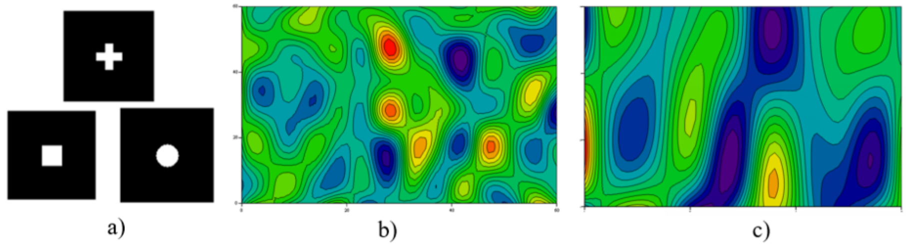



**Fig. 2.** Examples of an object (a), background radiation (b) and radiation attenuation by the air path (c), generated by the developed model.

$$F(x,y) = \left\{ f(x,y)M^{*}[H_{op}(u,v).H_{c}(u,v).H_{d}(u,v)]^{\Phi^{-1}} + \eta_{b}(x,y) \right\}. \\ .\eta_{w}(x,y) + \eta_{e}(x,y) \quad (10)$$

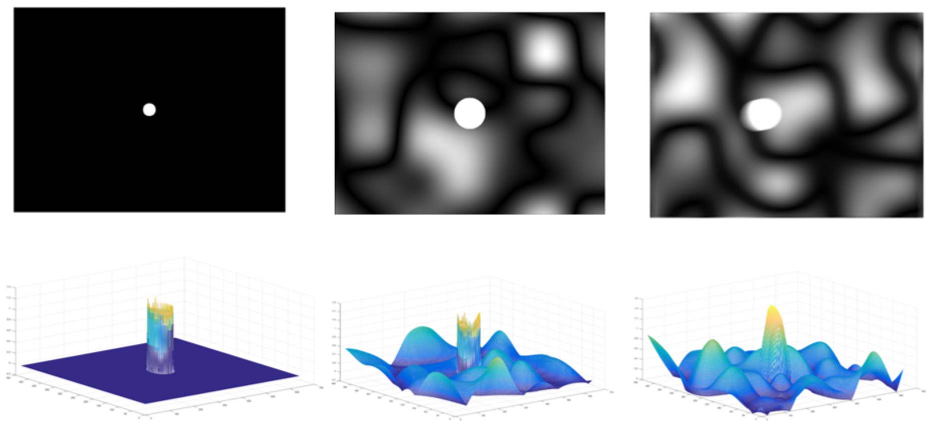
where f (x, y) - the function of the object form; M - is the function of the object scaling taking into account the distance H and focal distance f' of the optical system; $H_d(u,v)$ - transfer function for determining the spatial position of an object in an image with the translational property of the time delay of the Fourier transform, which ensures the spatial position of the object with the highest possible accuracy; $H_{op}(u,v)$ - is the weight function of the optical system; $H_c(u,v)$ - transfer function image blur; $\Phi^{-1}$ – Inverse Fourier transform; $\eta_b(x,y)$ – the function of forming the distribution of background radiation, taking into account the influence of the average ambient temperature; $\eta_w(x,y)$–is the forming function of the background irradiation, $\eta_e(x,y)$ - the receiver noises OES RMPC.

Based on the resulting function using Matlab and a library IPT (Image Processing Toolbox) [20] a program of RM image synthesis in OES RMPC was written. Modeling results are illustrated in Fig. 3.

## 5 Performance analysis of restoration methods of distorted RM images synthesized by the computer model

Modeling of the original RM position at 20 px smear length with RM image coordinates (319.15 px, 239.92 px) has demonstrated that the error of RM image coordinates definition for restored images is 0.0118 px for Wiener method, 0.0136 px for Tikhonov method, 0.0148 px for Lucy-Richardson method, and 0.0149 px for blind deconvolution method.

Results of applying restoration methods (3) – (6) of RM images are illustrated in Fig. 4.



a) b) c)

**Fig. 3.** RM image synthesized by a computer model in Matlab: a) an ideal RM image without noise; b) RM image distorted by noise and background; c) an image exposed to a smear caused by relative motion of OES RMPC and RM.

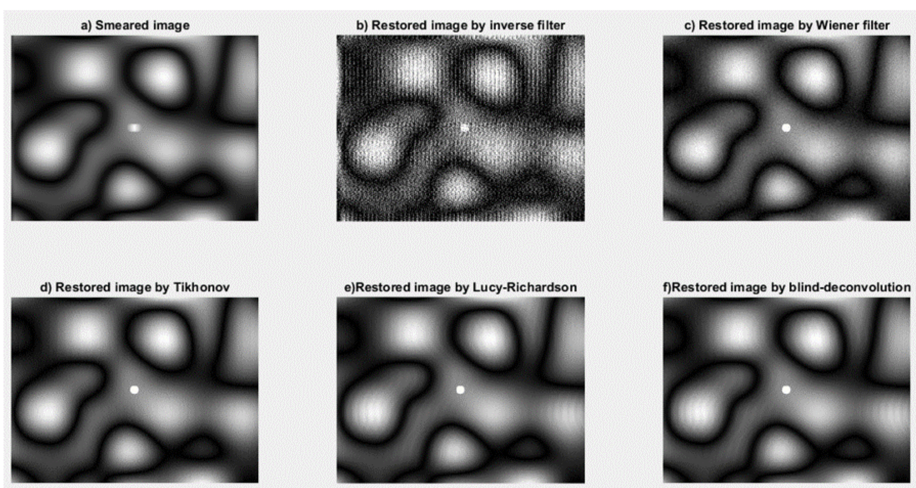



**Fig. 4.** Results of RM image coordinates definition with Matlab: a) coordinates of the smeared RM image energy center is (320.05 px, 240.57 px); RM image energy center coordinates in the image restored by b) inverse filtration are not defined; c) Wiener parametric filtration are (319.17 px; 239.93 px); d) Tikhonov method are (319.15 px; 239.93 px); e) Lucy-Richardson method are (319.13 px; 240.52 px); f) blind deconvolution are (319.12 px; 240.52 px).

Thus, application of different methods for RM image restoration has demonstrated that:

- inverse filtration (Fig. 3b) demonstrates significant distortions and doesn't allow to define energy center coordinates after image restoration;

- applying of Wiener parametric filtration (Fig. 3c) and the method of smoothing functional minimization (Tikhonov regularization) (Fig 3d) for image restoration has demonstrated the best results and advisability of their use in OES RMPC. Besides this, the developed computer model can be used for estimation of energy center shift evaluation, with irradiance in the receiver plane considered, as well as for optimization of OES RMPC parameters in accordance to operational conditions.

## 6 Conclusion

In the paper it is proven that the shift transfer function (7) can set a RM image position with the precision up to a hundredth of a pixel. Mathematical description of RM distorted image, with RM motion relative to the system considered, is developed.

It is discovered that applying of Wiener parametric filtration and the method of smoothing functional minimization (Tikhonov regularization) for image restoration demonstrate the best restoration results and can be recommended for use in the information processing system in OES RMPC.

Efficiency of applying the developed computer model to estimation of distorted RM image restoration methods is proven.

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