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An Aggregated Method for Determining Railway Defects and Obstacle Parameters

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Abstract. The method of combining algorithms of image blur analysis and stereo vision to determine the distance to objects (including external defects of railway tracks) and the speed of moving objects-obstacles is proposed. To estimate the deviation of the distance depending on the blur a statistical approach, logarithmic, exponential and linear standard functions are used. The statistical approach includes a method of estimating least squares and the method of least modules. The accuracy of determining the distance to the object, its speed and direction of movement is obtained. The paper develops a method of determining distances to objects by analyzing a series of images and assessment of depth using defocusing using its aggregation with stereoscopic vision. This method is based on a physical effect of dependence on the determined distance to the object on the obtained image from the focal length or aperture of the lens. In the calculation of the blur spot diameter it is assumed that blur occurs at the point equally in all directions. According to the proposed approach, it is possible to determine the distance to the studied object and its blur by analyzing a series of images obtained using the video detector with different settings. The article proposes and scientifically substantiates new and improved existing methods for detecting the parameters of static and moving objects of control, and also compares the results of the use of various methods and the results of experiments. It is shown that the aggregate method gives the best approximation to the real distances.

1. Existing Approaches

The stream of digital images may be used to determine the distance to a real-world object that manages the intellectual environment by using natural and intuitive communication of the information.

In modern computer vision systems ToIE (technology of intelligent environments) there are several ways to obtain additional information about the behavior and state of tracked objects: multisensory approach (stereovision) [1, 2], construction of image perspective [3], the use of fixed camera and additional lighting of the object [4], the use of methods of wave analysis [5-7], as well as a special video detector calibration [8-10]. Each of these methods could be used in practice depending on the task [11, 12]. Among the many methods for determining the parameters of behavior and state of a tracked object, the most popular are techniques of stereo vision; determination of blur for a given motion of the imaging detector; definition of blurring for different colors included in the Full HD image of the object. Each method has its advantages and disadvantages, most often associated with technical and software



opportunities. The paper develops a method of determining distances to objects by analyzing a series of images and assessment of depth using defocusing [7-9] using its aggregation with stereoscopic vision. This method is based on a physical effect of dependence on the determined distance to the object on the obtained image from the focal length or aperture of the lens. With regard to the problem of determining the external defects of the railway, the distance and speed of objects on the railway, a system using the presented method on track geometry car can be mounted (figure 1). For developed systems, it is proposed to use ontology-based interfaces [6], whose advantages are presented in the paper [7].



Figure 1. View from the track geometry car.

2. Method implementation

When the video detector focuses on the object at a certain distance, other objects that are closer or further the focal point, form a blur circle depending on the distance on the plane of the image. Blur of the image of the object can be different nature and be determined by motion of the object or detector, boundaries of the object on the image, an aggregate state of the object, as well as various settings of the video detector (focal length, shutter speed, and aperture). As the defining the relations between the main parameters of the video detector and the location of the object in the exposition the following expression is used [8]:

$$1/f = 1/D_{ob} + 1/D_{fip}, \quad (1)$$

where f – the focal length; D_{ob} – distance from a given point of the object to the lens of video detector; D_{fip} – the distance from the center of the lens to a focused image of the object.

In the calculation of the blur spot diameter it is assumed that blur occurs at the point equally in all directions [17]. According to the proposed approach, it is possible to determine the distance to the studied object and its blur by analyzing a series of images obtained using the video detector with different settings. Figure 2 (blue line) represents the averaged dependence of the blur from the distance to the object when using three video detectors and the distance to the object in the focus is 1.2 m. For more accurate estimates of the definition of geometric parameters of behavior and the state of the studied object a statistical approach to define specific parameters and to evaluate their accuracy is used. Object's blur is calculated as an average value for all measurements of blur σ_i of the object at points of its boundary:

$$\sigma = \frac{1}{n} \sum_{i=1}^n \sigma_i, \quad (2)$$

where n — the number of measurements.

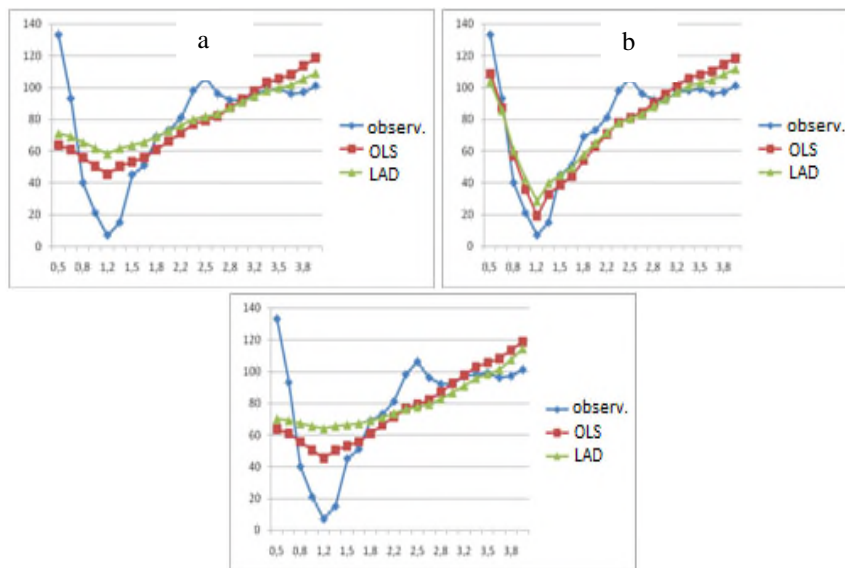


Figure 2. The dependence of the blur from the distance to the object for the standard functions:

a) linear; b) logarithmic; c) exponential.

The statistical approach to evaluate the deviation the dependence of the distance and the blur from the different types of standard functions (logarithmic, exponential, linear) (figure 2) is used. The statistical approach includes the method of least squares (OLS) and the method of least absolute deviations (LAD), as well as Bayesian estimates, for which it is necessary to minimize the risk for different loss functions (quadratic, rectangular, linear) [11,13].

$X = (X_1, \dots, X_M)^T$ – object location vector (distance to object) and $\theta_1, \theta_2, \dots, \theta_n$ – results of measurements of the average blur of an object. Each observation can be represented as a sum:

$$\theta_i = \eta_i(X) + \Delta_i, \quad (3)$$

where $\eta_i(X)$ – the known function, relative to the calculated estimate of the distribution; Δ_i – the measurement error.

To estimate the vector of the parameters of the distance to the object is proposed to use a class of statistical estimates M – estimates (that is estimates that provide the minimum sum of any of the functions from data):

$$X(\theta) = \arg \min_x \left(\sum_{i=1}^n L(\theta_i - \eta_i(X)) \right), \quad (4)$$

where $L(x)$ – the valuation function.

For least-squares estimation the function $L = z^2$ is used, by the method of least modules the function $L = |z|$ is used. According to the analysis of these estimates the function $\eta_i(X)$ closest to observations is chosen. The function $L(x)$ is chosen in such a way as to ensure the desired estimation properties (unbiasedness, consistency and efficiency) under conditions when data is taken from a known distribution, and the sufficient resistance to deviations from this distribution. The effectiveness of estimates relative to each other can be found by comparing the variances of estimates: the evaluation, whose dispersion is the smallest (i.e. less variance) is more effective. For sufficient resistance to deviations from the given function, it is necessary to build robust (sustainable) processing algorithms, that is, algorithms that are highly effective under conditions where the characteristics of the error distributions vary within the given classes.

There are two options for obtaining stable estimates of observations θ_i (3): a variation of a known function $\eta_i(X)$ with unknown error distribution Δ_i and using standard deviation of observations θ_i ; the use of the standard deviation for various functions of distributions of observation errors.

Using the methods of least squares and smallest modules, we estimate the unknown parameters of the chosen function $\eta_i(X)$. By substituting the functions of the linear form $\eta_i(X) = a + bx_i$, the estimated parameters \hat{a} and \hat{b} will be calculated according to the formulas:

$$\hat{b} = (\overline{x\theta} - \overline{x}\overline{\theta}) / (\overline{x^2} - \overline{x}^2); \quad \hat{a} = \overline{\theta} - \hat{b}\overline{x}, \quad (5)$$

where \overline{x} , $\overline{\theta}$, $\overline{x\theta}$ - the mathematical expectation of the distance to the object, the mathematical expectation of the measured observable values and their multiplication accordingly.

As a function $\eta_i(X)$ we consider linear, exponential, and logarithmic functions (figure 3):

$$\eta_i(X) = a + b|x - x_0|, \quad \eta_i(X) = a + b|\ln(x - x_0)|, \quad \eta_i(X) = a + b \exp(|cx - x_0|) \quad (6)$$

Assume that, based on the sample of the measurement results $\theta_1, \theta_2, \dots, \theta_n$, estimates are obtained: $X_1 = \theta_1^*$ (the OLS method) and $X_2 = \theta_2^*$ (the LAD method). In order to the final evaluation was unbiased and effective, one should choose the valuation method of processing observations that will give the least variation of estimates. Then the algorithm of final evaluation will be as follows:

$$X = W_1 X_1 + W_2 X_2; \quad W_i = \begin{cases} 1, & \text{if } D_i \leq D_j \\ 0, & \text{if } D_i > D_j \end{cases}; \quad i = 1, 2; j = 1, 2; j \neq i, \quad (7)$$

where D_i, D_j – selective variances of estimates by the OLS and the LAD algorithms.

3. An integrated approach based on the algorithms of stereovision and image blur

Simultaneously with the analysis of defocused images, it is also possible to use stereovision, then we can talk about an integrated approach to determining the characteristics of the objects. In this case, the features of two methods are taken into account, the parameters of methods are compared for further use in a single algorithm.

In the study of aggregation methods of stereovision and evaluation of the blur, it is necessary to determine the boundaries within which the methods should be used, to estimate the error of these methods and also to consider the possibility of replacing one method by another by introducing refinement coefficients. If the stereo vision system is configured accurately, then the adding of blur analysis method expands the limits of applicability of the method. If there are obstacles for one of the cameras or the scopes don't intersect in the system of stereo vision, the method of blur analysis also expands the applicability of the aggregate method.

Otherwise, blur analysis can be used to determine the refinement coefficient k from formula (7) by applying OLS. For this, it is necessary to consider the distance where it is possible to apply the blur analysis method, that is, where the error of this method is not more than the threshold of 5% (for example, when using cameras with 50 mm focal length the distance up to 3 m is considered), and at the same time it is necessary to memorize the difference of the object's location in the coordinate system of the left and right cameras using the method of stereo vision. The distances are calculated by formulas:

$$r_{\text{stereo}} = k \cdot f \cdot d / (\Delta x \cdot Sx); \quad r_{\text{blur}} = \eta(\sigma), \quad (8)$$

where $\eta(\sigma)$ – the function obtained from (4) with minimization of errors (from the results of the experiments $\eta(\sigma) = e^{(|(\sigma-a)/b|+0.2)}$).

So, we get:

$$\sum_N (r_{\text{blur}} - r_{\text{stereo}})^2 \rightarrow \min \quad (9)$$

Taking into account the above formula, we obtain for N observations in the range of distances where the use of the blur analysis method is most effective (up to 3 m or up to 6.5 m – given the camera's refocusing [8]):

$$\sum_N (\eta(\sigma) - k \cdot f \cdot d / (\Delta x \cdot Sx))^2 \rightarrow \min \quad (10)$$

Thus, we find the refinement coefficient k . In determining the distances at which the use of the blur analysis is impossible due to the large error, one can use the method of stereo vision with the use of the refinement coefficient k . The use of the aggregate method helps to increase the measured distance up to 10 m with an error of less than 5%. The accuracy of the proposed approach at such distances higher than separately applying of the blur analysis or method of stereovision without a refinement coefficient.

4. Results of experiments

The variances of errors and the mathematical expectation for each of the taken as known functions (6-9) are shown in figure 3. It is seen that the variance of the errors from function, the parameters of which are estimated by OLS will be less than the variance of the errors by LAD, that is, the estimate of the least squares is more stable. Also, the estimation of errors with the use of least squares is unbiased, while the mathematical expectation when using LAD is not zero, that indicates the bias of error estimates.

To smooth out possible “emissions”, we apply the Kalman filter to the initial observations and analyze estimations of OLS and LAD for the three functions discussed above after application of the filter.

The Kalman filter algorithm is based on induction and in the simplest case, when using a linear function as a theoretical function, it can be represented in the form of an iterative formula:

$$\theta_{k+1}^{opt} = K \cdot \theta_{k+1} + (1 - K) \cdot (\theta_k^{opt} + u_k), \quad u_k = \eta(x_{k+1}) - \eta(x_k), \quad (11)$$

where $0 \leq K \leq 1$ – Kalman coefficient; θ_k^{opt} and θ_{k+1}^{opt} – the current and the following filtered values of observations; θ_{k+1} – the following observation; u_k – a known value responsible for the evolution of the system, $\eta(x_k)$ and $\eta(x_{k+1})$ – the current and the following values of the theoretical function η .

For logarithmic and exponential functions, the equation will change due to the nonlinearity of the increments:

$$\theta_{k+1}^{opt} = K \cdot \theta_{k+1} + (1 - K) \cdot (\theta_k^{opt} \cdot u_k), \quad u_k = \eta(x_{k+1}) / \eta(x_k), \quad (12)$$

As the initial filtered observation the first observation is taken, i.e. $\theta_1^{opt} = \theta_1$. Using Kalman filter it is possible to reduce the error variance by appropriately selecting the coefficient K in the filter. Using the method of least squares and the method of least modules we will estimate the parameters of the function $\eta_i(X)$ in different dependencies of the observations, passed through the Kalman filter (figure 3).

Thus, using the Kalman filter and taking into account the variation of its coefficients in the analysis of the obtained functions the error distributions have a smaller variance, than without the use of a Kalman filter, that is, the evaluation is more efficient, hence it can be concluded that the Kalman filter provides an opportunity to obtain a more accurate theoretical function. Estimate with the least variance is the OLS estimation for the theoretical function (7) with parameters $a = 10.696$, $b = 93.122$ using the Kalman filter with coefficient $K=0.1$.

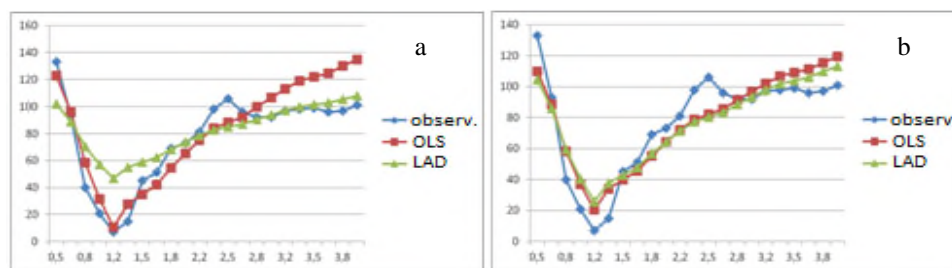


Figure 3. Dependence of the variance of the distance for a logarithmic model with the coefficient Kalman: a) – with coefficient $K=0.1$; b) – with coefficient $K=0.7$.

5. Results of using the combined method

The limits of applicability of the method depend on the selected focal length of the camera, exposure and pixel size of CCD matrix camera, stereobase. For the focal length of 50 mm and stereobase – 0.05 m, the limits of applicability of the developed method are presented in figure 4.

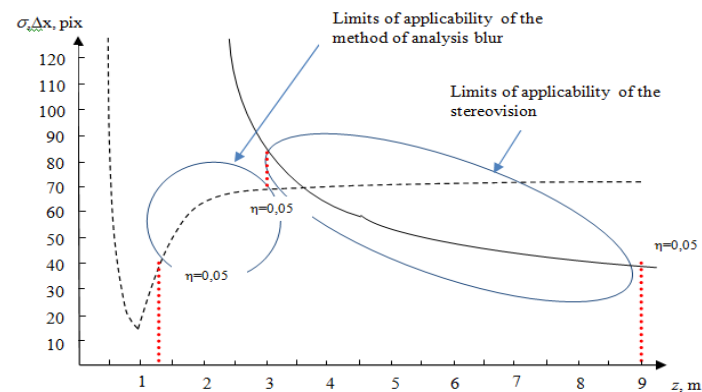


Figure 4. Limits of applicability of aggregated method.



Figure 5. Detection of external railway defects.

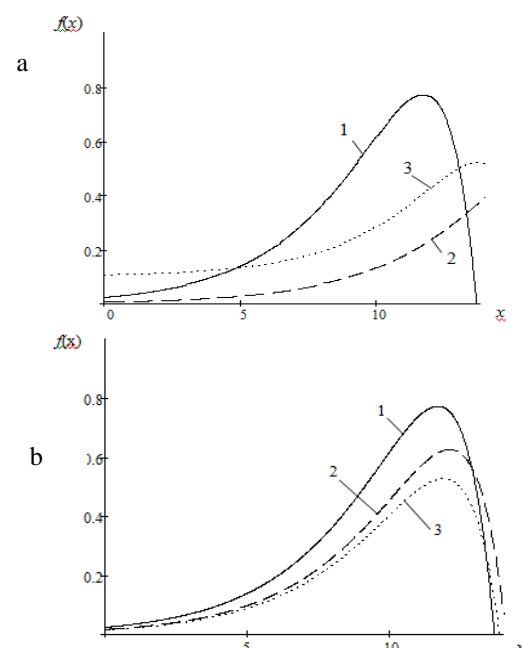


Figure 6. Dependence of accuracy of the distance determination to an object for different methods (a), for different focal lengths of video cameras (b).

The operation of the system under real conditions for detection of railway defects is presented in figure 5.

Figure 6a shows that using the combined method (curve 1) the accuracy of the measurement of the distance to the object is substantially increased in comparison with the methods based on stereo vision (curve 2) and the estimation the blurring of the image of the identified object (curve 3). The actual distance to the object at the time of photographing is 11.8 m. In figure 6b, a comparative analysis of the accuracy of determining the distance to the object with a change in the focal length: curve 1 corresponds to the focusing point at 11.0 m, curve 2 – 11.5 m, curve 3 – 10.5 m.

6. Conclusion

Studies have shown that for determination of parameters of the function which most accurately describes the dependence of the distance to the object from the blur, the optimal method is the method of least squares. The article proposes and scientifically substantiates new and improved existing methods for detecting the parameters of static and moving objects of control, and also compares the results of the use of various methods and the results of experiments. It is shown that the aggregate method gives the best approximation to the real distances. In general, the method proposed in this paper for determining the geometric characteristics of an object from the analysis of its image and the algorithm of estimation the values obtained with its help can be used in complex monitoring, diagnostic and control systems.

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