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METHODS OF COMPENSATION OF MICROBOLOMETER MATRICES SELF-HEATING IN THE PROCESSING OF THERMAL IMAGES

Abstract. The sources of noise and artifacts arising during thermal imaging and the methods for thermal images filtering, including methods specific for processing of images generated by infrared sensors, are considered. In particular, distortions caused by the process of microbolometrer matrices self-heating due to internal and external heating sources and the methods for compensating such distortions are studied. **The purpose of the study** is to create a mathematical model of a bolometric matrix self-heating based on heat transfer equations and to develop an algorithm for suppressing of distortions introduced into thermal images by self-heating. The exponential models describing the propagation of heat in the microbolometer matrix are proposed and it is shown that the coefficients of the models after logarithming can be determined by the least squares method. For real thermal images, the coefficients of the model are determined, and situations are considered when the base temperature of the object is known and when it is necessary to restore it, and modifications of the exponential model in the form of an exponent from a complete and incomplete square are proposed. Computer simulation of the proposed distortion compensation algorithm has been carried out, a set of thermal images before and after processing has been presented, and a quantitative estimation of the degree of noise suppression caused by heating of bolometric arrays has been obtained. Based on **the results of the work**, it was determined that the exponential model provides a sufficient degree of closeness of the experimental and theoretically predicted temperature data, and the degree of difference between the data and the model was estimated. Recommendations are developed for the application of the proposed methods at known and unknown base temperature of the matrix. Proposals have been developed for further improving the mathematical model, including the situation of temperature changes over time, and for improving the efficiency of self-heating noise suppression algorithms.

Keywords: thermal imaging; image processing; median filtering; microbolometric matrix; self-heating; mathematical model; least squares method.

Introduction

The emergence of commercial thermal cameras (thermal imagers), which are characterized by low price and size parameters, has greatly expanded the possibilities of remote non-contact temperature measurement in cases where it is necessary to monitor and control the thermal condition of objects with heat fluxes. The process of heat energy transfer, evolution or absorption of heat in the object leads to the fact that its temperature changes relative to the environment. The main parameter that carries information about the mode of operation of the object and defects in thermal monitoring is the temperature distribution over the surface of the object.

Thermal imaging are widely used in power engineering, construction and industry, as well as in the military. To register the state and monitor objects distributed over a large area (large industrial facilities and networks, agriculture and forestry) methods of automated monitoring using unmanned aerial vehicles (UAVs) are used [1]. In the process of automatic monitoring of power transmission lines, thermal imagers are usually installed on robotic platforms together with visible range cameras [2], and they allow to identify potential problems on insulators or power lines. In [3], it is noted that it is difficult to accurately measure the temperature of small objects, such as power line elements, even from a short distance.

Modern thermal imagers, as a rule, are made on the basis of special matrix temperature sensors - bolometers, while commercial bolometers are usually made uncooled to reduce the cost and size of equipment. The paper [4] shows the theoretical possibility of using thermal imagers with uncooled bolometric matrices for non-contact measurement of the temperature of power line wires and presents a method for determining the state of conductors by thermogram.

The mentioned papers emphasize that the methods of using thermal imagers for thermal monitoring of industrial infrastructure facilities are insufficiently developed and need further improvement.

Thus, the development of algorithms to reduce the influence of unfavorable external factors, to increase the accuracy of measurements and the reliability of identifying objects in thermal images is relevant.

Overview of noise and interference sources in thermal images and existing methods of their filtering

A significant number of works by domestic and foreign scientists are devoted to the analysis of sources of noise, interference and artifacts on thermal images and methods of reducing these interferences. Thus, in [5] possible noises arising at the analysis of thermal images is analyzed. It is shown that, depending on the type of sensors used and the experimental conditions, all the main types of noise such as Gaussian, Poisson, salt and pepper, speckle noise are possible. In these cases, the measurement process is affected by weather conditions and interference on thermograms, which are caused both by the properties of the materials of objects and by the peculiarity of the functioning of thermal imagers (self-heating, low resolution, various defects).

In [6], the issues of using thermal imaging equipment to detect and control fires at industrial enterprises are considered. The factors that complicate the process of automated detection of objects are indicated: noisiness of useful signals not only by additive white Gaussian noise, but also by specific multiplicative noise, insufficient image contrast in comparison with visible range devices, high inertia of microbolometer sensors causes the effect of distortion of the shape of the object called "rolling shutter" [7].

To suppress noise, it is proposed in [6] to use the adaptive Kalman filtering and the adaptive median filtering. Thermal image processing, however, failed to overcome their traditional disadvantages: sensitivity to rounding errors for the Kalman filter, cutting corners on graphic objects, and insufficient suppression of white Gaussian and fluctuation noise for the median filter. Linear filtering of biomedical images in the infrared range, proposed in [8] to suppress additive noise and highlight objects, can cause loss of sharpness and blurring.

It is proposed in [9-12] to jointly solve the problem of filtering impulse interference and increasing the image contrast. In [9] the concept called *Background Thermal Compensation by Filtering, BTCF* is introduced, in [10] - the method of fast noise suppression. These technologies are implemented by dynamically selecting the size of the filtering window and decimation of the filtered sequence.

In [11, 12], together with median filtering, it is expected to use histogram equalization to increase the contrast of thermal images. At the same time, in [12], the histograms are equalized after an additive wavelet transformation in each subband separately, which allows to increase the contrast and to simplify the procedure of Sobel edge detection.

The disadvantages of the methods developed in [9-12] are typical for traditional median filtering - the complexity of adapting the degree of noise suppression to the level of noise in individual areas of the image and significant computational complexity, which makes it difficult to implement the developed algorithms in real time.

Thus, the insufficient performance of widely used microcontrollers required the authors of articles [13, 14] to construct a module for processing thermal images based on field-programmable gate arrays (FPGA) ALTERA. The module proposed in [13] provides two-dimensional FIR and median filtering, dynamic range expansion and pixel operations, the module described in [14] also implements affine transformations and provides thermal image processing at a rate of 12 to 46 frames per second. FPGA implementation of the proposed modules, however, complicates the dynamic correction of the algorithm during operation.

[15-16] consider the problem that does not arise when processing images in the visible part of the spectrum - uneven heating of microbolometric matrices caused by both external heat sources and heat fluxes emitted by elements of thermal imaging equipment. This phenomenon, called self-heating in [15-16], leads to distortions in thermal images - areas of abnormal brightness, usually at the edges and corners.

In order to reduce this problem in [15] it is proposed to construct a polynomial model of matrix heating, in [16] a model of heat distribution taking into account the substrate temperature is proposed. The values predicted on the basis of the constructed models can be used to correct the thermal iimage. A similar method of self-heating compensation distributed in lenses and infrared detectors is given in [17]. In [18] a model is proposed taking into account the electrical parameters of the microbolometric matrix. However, the results of the experiment presented in [15-18] demonstrate that the constructed models do not provide sufficient accuracy.

The aim of the article is to construct mathematical models of self-heating of the bolometer matrix in different conditions, to develop methods of correction of thermal images taking into account additionally introduced heat and to experimentally study the proposed algorithms.

Construction of a mathematical model of the self-healing process

Analysis of thermal images shows that the source of self-heating is primarily the corners of the matrix, that is, we assume that there is an instantaneous point source of heat. As shown in [19], in this case, as a result of solving the equation of thermal conductivity, we can obtain expressions for the value of the temperature for any point of a rectangular plate:

$$T(R,t) = \frac{Q}{c\cdot(4\pi\alpha t)^{3/2}}\cdot\exp\left(-\frac{R^2}{4\alpha t}\right)+T_0, \qquad (1)$$

where T – is the temperature of the studied point of the object y with coordinates x, y; T_0 – is temperature of the object at the initial moment of time; R – is the distance from the studied point of the object y A to the point of heat input O. If we assume that the origin of coordinates is at the point of heat input, $R=\sqrt{x^2+y^2}$; t – is the time since the moment of heat input, with, s.; c – is the specific volume heat capacity, J/(m^3·K); Q – the introduced amount of heat, J; α – is the coefficient of thermal conductivity, m^2/s.

We fix a moment of time t and enter the coefficients

$$A=\frac{Q}{c\cdot(4\pi\alpha t)^{3/2}}, \qquad \lambda=-\frac{1}{4\alpha t}.$$

Then the dependence of the temperature at some point of the plate from the distance of this point to the corner (origin of coordinates) will look like:

$$T(R) = A\cdot\exp\left(-\lambda R^2\right)+T_0 = \exp\left(\lambda R^2+\mu\right)+T_0, \quad (2)$$

where $\mu = \ln A$.

Using the obtained equation, we can try to determine the coefficients of the model (1) by the values of temperature at individual points, to calculate the excess values of temperature introduced due to self-heating and to compensate them.

Determining the required coefficients by the least squares method can be difficult, and logarithmizing the sum in (2) is impossible. The most successful option may be to determine the base temperature T_0, for example, by periodically measuring the temperature in the center of the thermal image (point C) in the absence of an object.

Then the temperature dependence takes form

$$T'(R) = T(R)-T_0 = \exp\left(\lambda R^2+\mu\right). \quad (3)$$

After logarithmization (3) takes the form

$$\theta(R) = \ln T'(R) = \lambda R^2+\mu. \quad (4)$$

Using the least squares method, we can find the unknown coefficients λ and μ in (3), obtain the probable distribution of excess heat entering the matrix as a result of self-heating, compensate it and reduce the level of interference and artifacts in thermal images.

Figure 1 shows a thermal image of a uniformly heated plate (temperature is displayed in arbitrary units in the range from 0 to 1). In the absence of interference, self-heating and other artifacts, the image should be uniform, but the above mentioned factors lead to the appearance of warmer (lighter in the image) areas at the edges of the plate.

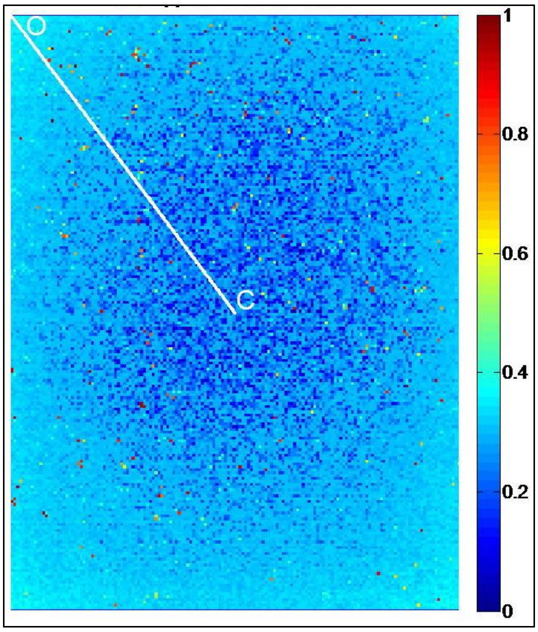

Fig. 1. Thermal image of a uniformly heated plate

To construct the model we take as the points of heat input O the corners of the plate and draw from each of the plate corners the rays towards the plate center, point C. Temperature values measured at points along the ray OC form the temperature dependence from the distance from the plate corner in Fig.2). At the same time, in order to suppress impulse noise that complicate further processing, the thermal image is subjected to median filtration [6].

Experimental research of the developed method

By measuring the temperature at point C of the plate and subtracting it from all values of the temperature on the OC ray, we obtain a data set suitable for constructing a model. According to the expressions (2) - (4), we logarithm the sequence of samples and reconstruct the unknown coefficients of the polynomial model (4) by the least squares method.

For the considered upper left corner of the thermal image in Fig. 1 the temperature in the center of the plate will be T_0 = 0,2631, the coefficients of the model (4):

$$\lambda = -\,1{,}6807\cdot 10^{-5}, \quad \mu = -2.5293.$$

Thus, according to (2), the temperature dependence takes the form:

$$T(R) = \exp\left(\lambda R^2+\mu\right)+T_0 = \exp(\mu)\cdot\exp\left(\lambda R^2\right)+$$
$$+T_0 = 0{,}0797\cdot\exp(-1{,}6807\cdot 10^{-5}\cdot R^2)+0{,}2631. \quad (5)$$

The dependence made according to the formula (5) is shown by a dash-dotted line in Fig. 2.

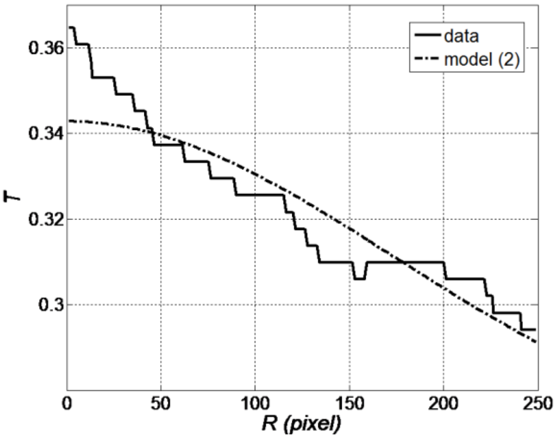

Fig. 2. Experimental and theoretical (2) dependences of temperature on the distance to the corner of the plate

In this case, the input excess heat will be

$$T'(R) = T(R)-T_0 = \exp\left(\lambda R^2+\mu\right) =$$
$$= 0{,}0797\cdot\exp\left(-1{,}6807\cdot 10^{-5}\cdot R^2\right). \quad (6)$$

Rays can be drawn in a similar way and and models can be constructed for the other three corners of the thermal image matrix.

By calculating similarly (6) for each of the corners and a quarter of the adjacent image, the amount of additional heating, we subtract the values obtained from the temperature distribution matrix that forms the thermal image. The processed image, on which the distortions due to self-heating are partially compensated, is shown in Fig. 3.

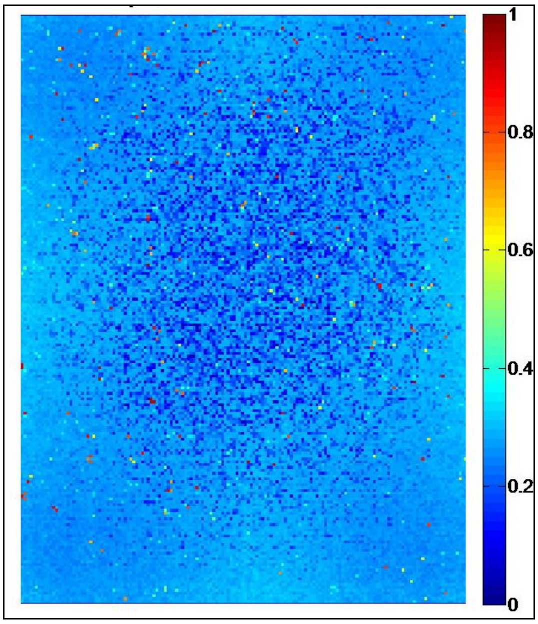

Fig. 3. Thermal image of a uniformly heated plate after processing

Comparing Fig. 1 and 3, it can be seen that the distortions due to self-heating, which look like the lighter areas adjacent to the corners, in Fig.3 are significantly weakened.

The degree of suppression of distortions can be quantified. In the absence of interference and artifacts, the entire surface of the plate must have the same temperature, that is, the temperature values at all points of the image must coincide with the temperature in the center of the matrix T_0. Then the relative mean square error will be defined as:

$$\varepsilon = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(a_{ij}-T_0\right)^2} \Big/ \left(N\cdot M\cdot T_0\right), \qquad (7)$$

where N, M – are the height and width of the image, respectively, a_{ij} – is relative value of temperature at the point of the image.

For the analyzed image, the values of the relative error will be: before processing ε_1=0,023, after processing ε_2=0,016.

Thus, the degree of interference suppression will be equal $k_i=\varepsilon_1/\varepsilon_2$=1,4375.

If it is possible to measure the base temperature in the center of the image, the described technique can be used to process thermal images containing objects that differ sharply in temperature from the background.

An example of such an image is shown in Fig. 4. Obviously, it is difficult to determine the base temperature. In this case, as in Fig. 1, in the corners and edges of the image we can see the results of self-heating, which are manifested as lighter areas.

Since the measurements were made under the same conditions, the models (5) and (6) obtained above and the coefficients can be used in this case as well. As in the previous case, we calculate by formula (6) and the values of the introduced heating by similar to it, and compensate the distortions introduced due to self-heating. The results of processing are shown in Fig. 5.

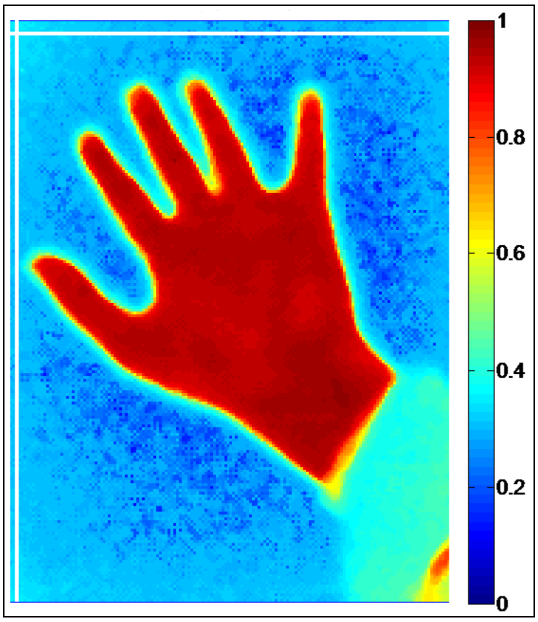

Fig. 4. Thermal image containing a contrast object

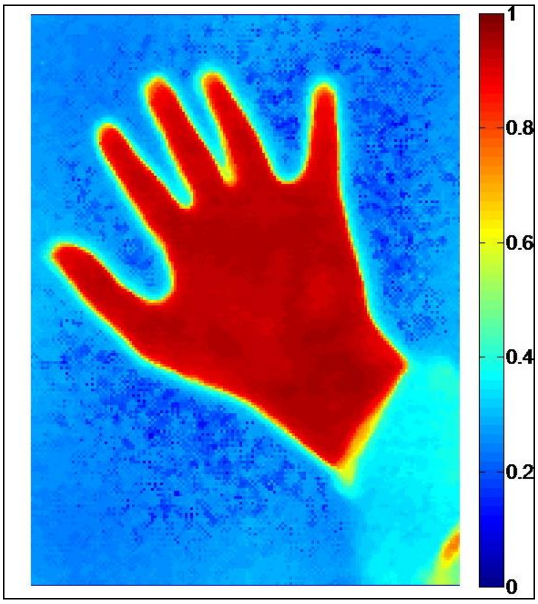

Fig. 5. Processed image containing a contrast object

The figure shows that, as in the case of a uniformly heated plate, the distortions introduced due to self-heating are weakened.

However, it is not always possible to determine the base temperature T_0.

In such cases, it is appropriate to modify the heat distribution model.

We choose as a model the ratio

$$T(R)=\exp\left(\lambda R^2+\nu R+\mu\right). \qquad (8)$$

As in the previous case, we logarithm (8) and obtain a polynomial dependence

$$\theta(R)=\ln T(R)=\lambda R^2+\nu R+\mu, \qquad (9)$$

for finding the coefficients of which we can use the least squares method. Then it is still possible to get a picture of the distribution of excess heat and compensate its effect on the thermal image.

As the basic value of temperature, the point in which function (8) takes the minimum value, that is, size can be chosen $T\left(-\nu/(2\lambda)\right)$.

If it is difficult to construct model (8) in any of the corners and the results predicted by the model deviate significantly from the initial data (for example, the lower right corner in Fig. 4), the model coefficients can be taken from another corner where the best compliance is provided.

According to the proposed algorithm, the image in Fig. 4 was proccessed. Construction of the model (8) of heat distribution in a rectangular plate for one of the corners is shown in Fig. 6.

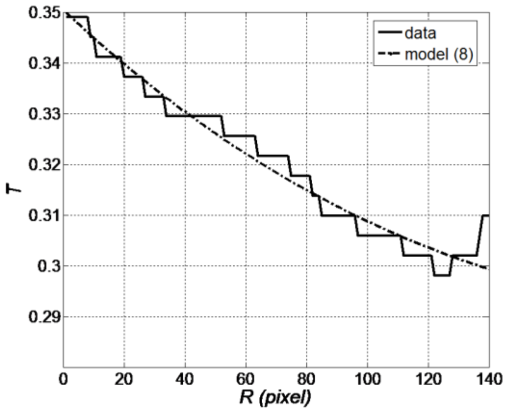

Fig. 6. Experimental and theoretical (8) dependences of temperature on the distance to the corner of the plate

After logarithmization of the data and application of the least squares method, the coefficients of the model are determined:

$$\lambda = 3{,}471 \cdot 10^{-6}; \quad \nu = -0{,}0016; \quad \mu = -1{,}0484.$$

$$T_0 = T\left(-\frac{\nu}{2\lambda}\right) = T(230{,}478) = 0{,}3003.$$

For each of the corners, the coefficients of the model (8) are calculated and the distortions introduced due to self-heating are compensated. The results of processing are shown in Fig. 7.

Visual analysis shows that image distortion caused by heat is largely eliminated, although not as in Fig. 5.

To assess the distortions introduced due to self-heating and the degree of their suppression, it is appropriate to analyze the temperature distribution along a single row or column of the image. The smoothed curves corresponding to the change in temperature along the twentieth row and the tenth column of the image (highlighted in Fig. 4) are shown in Fig. 8. The figure shows that the temperature rise towards the edges of the image, which is clearly visible on the initial curves and caused by self self-heating, are largely suppressed after processing.

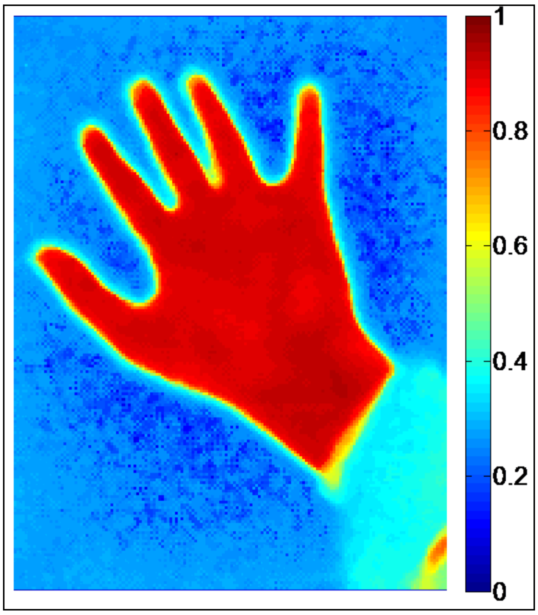

Fig. 7. The image processed according to (8)

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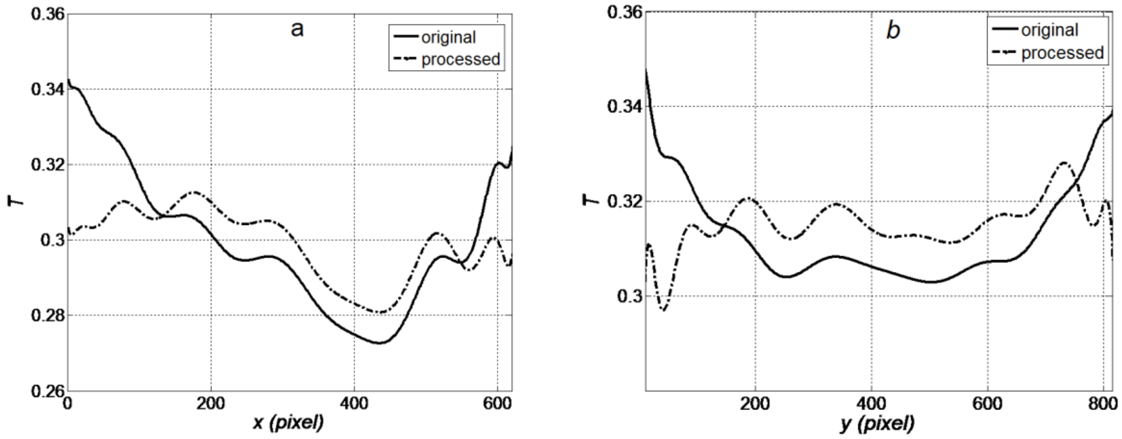

Fig. 8. Temperature distribution along the twentieth row (a) and the tenth column (b) of the image before and after processing

The figure shows that the temperature rises towards the edges of the image, which is clearly visible on the initial curves and caused by self-heating, are largely suppressed after processing.

Conclusions

1. The process of self-heating of the microbolometric matrix can cause distortions in thermal images, which complicate the analysis and detection of objects in the images.
2. Exponential mathematical models quite accurately describe the process of self-heating of the microbolometer matrix.
3. The use of constructed models allows to compensate the distortions caused by the effect of self-heating on thermal images and to reduce the interference level by 44%. In this case, the efficiency of the method increases if it is possible to determine the base temperature in the center of the image.
4. It is possible to refine the model by taking into account the input of excess heat not only from the corners but also from the edges of the microbolometric matrix. In addition, it would be relevant to study the dynamics of the behavior of the model coefficients over time in order to predict and compensate distortions.

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Методи компенсації самонагріву мікроболометричних матриць при обробці тепловізійних зображень

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Анотація. Розглянуто джерела шумів та артефактів, що виникають при побудові тепловізійних зображень та методи їх фільтрації, у тому числі методи, специфічні для обробки зображень, що формуються датчиками інфрачервоного випромінювання. Зокрема, досліджено спотворення, спричинені процесом самонагріву мікроболометричних матриць, обумовленого внутрішніми та зовнішніми джерелами нагрівання та методи компенсації таких спотворень. **Метою дослідження** є побудова математичної моделі самонагріву болометричної матриці на основі рівнянь теплопередачі та розробка алгоритму придушення спотворень, що вносяться самонагрівом у тепловізійні зображення. Запропоновано експоненціальні моделі, що описують розповсюдження тепла в мікроболометричнійй матриці, показано, що коефіцієнти моделей після логарифмування можуть бути визначені методом найменших квадратів. Для реальних тепловізійних зображень визначено коефіцієнти моделі, причому розглянуті ситуації, коли базова температура об'єкта відома і коли необхідно її відновлення, а також запропоновані модифікації експоненційної моделі у вигляді експоненти від повного та неповного квадрата. Проведено комп'ютерне моделювання запропонованого алгоритму компенсації спотворень, представлено набір тепловізійних зображень до та після обробки та отримано кількісну оцінку ступеня придушення перешкод, обумовлених нагріванням болометричних матриць. За **результатами роботи** визначено, що експоненціальна модель забезпечує достатню міру близькості експериментальних та теоретично передбачених температурних даних та оцінено міру розбіжностей між даними та моделлю. Розроблено рекомендації щодо застосування запропонованих методів за відомої та невідомої базової температури матриці. Вироблено пропозиції щодо подальшого уточнення математичної моделі, у тому числі в ситуації зміни температури за часом, та підвищення ефективності алгоритмів придушення перешкод, спричинених самонагріванням.

Ключові слова: тепловізори; обробка зображень; мікроболометрична матриця; самонагрів; математична модель; медіанна фільтрація; метод найменших квадратів.

Методы компенсации самонагрева микроболометрических матриц при обработке тепловизионных изображений

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Аннотация. Рассмотрены источники шумов и артефактов, возникающих при построении тепловизионных изображений и методы их фильтрации, в том числе методы, специфичные для обработки изображений, формируемых датчиками инфракрасного излучения. В частности, исследованы искажения, вызванные процессом самонагрева микроболометрических матриц, обусловленного внутренними и внешними источниками нагрева и методы компенсации таких искажений. **Целью исследования** является построение математической модели самонагрева болометрической матрицы на основе уравнений теплопередачи и разработка алгоритма подавления искажений, вносимых самонагревом в тепловизионные изображения. Предложены экспоненциальные модели, описывающие распространение тепла в микроболометрической матрице, показано, что коэффициенты моделей после логарифмирования могут быть определены методом наименьших квадратов. Для реальных тепловизионных изображений определены коэффициенты модели, причем рассмотрены ситуации, когда базовая температура объекта известна и когда необходимо ее восстановление, а также предложены модификации экспоненциальной модели в виде экспонента от полного и неполного квадрата. Проведено компьютерное моделирование предложенного алгоритма компенсации искажений, представлен набор тепловизионных изображений до и после обработки и получена количественная оценка степени подавления помех, обусловленных нагреванием болометрических матриц. По **результатам работы** определено, что экспоненциальная модель обеспечивает достаточную степень близости экспериментальных и теоретически предсказанных температурных данных и оценена степень расхождений между данными и моделью. Разработаны рекомендации по применению предложенных методов при известной и неизвестной базовой температуре матрицы. Выработаны предложения по дальнейшему уточнению математической модели, в том числе в ситуации изменения температуры по времени, и повышению эффективности алгоритмов подавления помех, вызванных самонагреванием.

Ключевые слова: тепловизоры; обработка изображений; медианная фильтрация; микроболометрическая матрица, самонагрев; математическая модель; метод наименьших квадратов.