Modern Applied Science; Vol. 9, No. 2; 2015
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

# Cuboids of Infrared Images Reduction

Igor' Ishchuk[1], Andrey Parfiriev[2], Valery Tyapkin[1], Mikhail Semenov[2,3,4] & Evgenia Kabulova[4]

[1] Siberian Federal University, Krasnoyarsk, Russian Federation

[2] Meteorology Department, Zhukovsky–Gagarin Air Force Academy, Voronezh, Russian Federation

[3] Voronezh State University of Architecture and Civil Engineering, Voronezh, Russian Federation

[4] Stary Oskol technological Institute named after A. Ugarov (branch) National University of Science and Technology "MISIS", Stary Oskol, Russian Federation

Correspondence: Evgenia Kabulova, Belgorod region, Stary Oskol, Russian Federation. Tel: 7-951-132-9959. E-mail: evgenia.kabulova@mail.ru

Received: November 13, 2014 Accepted: November 27, 2014 Online Published: January 10, 2015
doi:10.5539/mas.v9n2p206 URL: http://dx.doi.org/10.5539/mas.v9n2p206

## Abstract

The main idea of this scientific article is tomography usage. Projections of multidimensional signal carrying the information about the spatial structure of objects' thermal physic properties are represented by thermal tomograms obtained in active mode of test material surface heating by infrared radiation.

Processing of a thermal tomogram is produced by solving the inverse thermal conductivity problem. This solution applies to cuboids of infrared images reduction class of problems. Because of reduction, we get the distribution image of thermal conductivity identified values on isotropic material surface (thermal tomogram) allowing revealing foreign inclusions in the heterogeneous object structure based on the contrast over thermal conductivity. Implementation of this idea is associated with certain difficulties due to the necessity of mathematical modeling of nonlinear thermal transients.

The paper presents quartz sand thermal tomograms with temperature conductivity of 9 10-7 m2 s and thermal conductivity of -1 0.9 W m-1 K-1 which structure contains thermal insulation material - expanded foam, and thermally conductive material - aluminum.

**Keywords:** thermal physic parameters, cuboids of images, coefficient inverse problem, mathematical modeling, thermal tomogram

## 1. Introduction

Recently, the method of thermal non-destructive control is experiencing high growth, dramatically increasing the number of diagnosed objects. Development and implementation of thermal control methods can solve the problem of technical condition diagnostics from 30 to 50% of various products and materials, including those that can not be controlled by traditional methods. The main advantages of thermal method include:

large list of control objects;

remoteness of control or sensing objects, including dangerous objects;

high performance and safety of works;

possibility of passive control at one-way access to the object;

possibility of automation and hardware implementation of thermal control systems operating in real time;

relatively small financial cost of development, creation of software and hardware and implementation of control procedures.

It is known that thermal nondestructive control of tasks in the aerospace, nuclear, municipal, metallurgy, petrochemical, energy, environmental and other industries is divided into two direction:

detection and characterization of defects in materials and products made of them (from metals to multilayer structures) and registration of leaks and damages in polymers and composites;

diagnostics of technical condition and heat-emitting objects quality control, stress states of bearing structures, etc.

Research in the field of infrared thermography application in solving problems on detecting defects started in the period of 1960-1970s, when optronic infrared (IR) spectrum system were applied in aerospace technology and nuclear energy industry.

In recent years, we can talk about the rapid development of thermal nondestructive control methodology and its intensive implementation into industrial practice. The main factor for this became a new generation of infrared instruments: high-speed thermal imagers with uncooled bolometers, high-precision radiometers, thermographers. At that, it is considered almost standard to install microprocessors of preliminary data processing and coupling interfaces with computer via high speed channels Fair Ware, Line or RS-232 at such infrared devices.

According to its physical nature, thermal nondestructive control is based on direct methods for solving the problem of heat conductivity for multilayer objects. The analytical approach allows qualitatively assessing of time, power of thermal radiator, depth and thickness of the defect, its thermal properties. Numerical methods for passive stationary tasks of nondestructive control can quantify the topology of the temperature field and thereby identify local anomalies on the surface of a controlled object and associate them with the parameters of internal defect. As for active non-stationary problems, thermal nondestructive control allows consideration of temporal characteristics of the radiator and temperature fields, and algorithms for the solution of the direct problem of heat conductivity enable to estimate the possible parameters of thermal methods for detection of defects by computational way and with reasonable accuracy and thereby reduce the amount of experimental research.

Along with the intensive introduction of thermal nondestructive control in almost all sectors of industry, there are researches on the use of infrared thermography to locate an object in the ground - definition of its shape and size on the results of measurements of the thermal field. In the most responsible cases, the problem of object recognition using its "image" - a map of the measured reference images of typical objects, is solved by methods of neural networks, the calculation of the cross-correlation and those related to them. This approach is essentially based on the analysis of the existing database of measurements regardless of the physical processes involved, and the recognition of a new type of object is associated both with the completion of the database, and with the "learning of the detector" - complement of the rules system by defining recognition algorithm.

But the theory and practice of thermal exchange processes in thermal design and simulation of thermal modes of technical systems contains a rapidly developing the area of research based on the principle of inverse thermal conductivity problems. These methods gained special distribution during the experimental study of transient thermal processes for remote determination of thermal physic parameters of isotropic materials using thermal imaging equipment, operating in the infrared range of 8-12 μm (Hartless et al., 1991; Ishchuk et al., 2009; López et al., 2014).

The majority of currently applied measurement units of active thermography use comparison of thermal tomograms obtained with reference images (Maldague, 1993; Ringermacher, 2012). Some researches use laser in addition to infrared pulse emitter (Broberg and Runnemalm, 2012). The proposed method of processing dynamic infrared images of objects based on the general physical and systemic principles of appropriate mathematical models of physical objects with the use of standards, variations calculations, offset and iterations, and, in addition, the principle of detection by thermal parameters.

## 2. Literature Review

Considerable attention is paid to the method of obtaining spatial and temporal distribution of radiation temperatures (cuboids of infrared images). It consists in the idea of application of the active pulse heating of the surface under study from a source of infrared radiation to a temperature corresponding to the upper limit of sensitivity of an imaging infrared detector. In addition, it includes recording of the radiation temperature during the active heating and cooling periods within its spatial resolution (Ishchuk et al., 2009, 2014).

However, the majority of the above-mentioned works (López et al., 2014) use a simplified solution of the direct thermal conductivity problem utilizing empirical relationships. Thus, the article by Vavilov (Vavilov, 2012) demonstrates the use of simplified analytical expressions for semi-infinite substrate plate. Davis and Venkatraman in their paper (Davis and Venkatraman, 2012) substitute heat transfer task with the simplified solution in the form of electrothermal analogy: heat flow through the steam pipe is simplified and resolved using concept of thermal resistance. At that, the researchers do not consider inverse thermal conductivity problem for resolving the problem of finding a defect.

## 3. Materials and Methods

Let us develop a model situation for obtaining cuboids of infrared images shown in Figure 1, where 1 is isotropic medium; 2 is infrared heating source, providing pulsed heating of the isotropic medium surface; 3 is imaging infrared detector; 4 is superheat-conducting material; 5 is insulation material.

The considered works do not take into account the input of thermal and physical parameters in formation of thermal contrasts. This leads to the fact that, for example, as a result of surveying performed in the daytime on a clear day, and decoding infrared images of the set area obtained at night during adverse weather conditions (presence of cloudiness, precipitation, wind gusts, etc.) or after a long time, may give different results.

Research in the field of detection of objects in the infrared wavelength range are in very active state, both experimentally (López et al., 2014; Štarman et al., 2008; Swiderski, 2012), and theoretically (Vavilov V. 2012). We consider a variety of models, and solutions are obtained depending on the material, shape and size of objects, environmental conditions, etc. The authors studied the thermal dimensional model of soil and carried out the study concerning daytime and annual changes in surface temperature depending on heating conditions and soil moisture. Taking into account the periodicity of solar heating, daytime surface temperature of the soil is represented as a function of its geological, topographical and solar-atmospheric properties.

The article by (Winter E.M., 2004.), based on the numerical solution of the equation of heat transfer for the one-dimensional model of the soil by finite element method, studies measure the energy of the soil brightness depending on the humidity and time of the day.

These studies consider both two and three-dimensional thermal patterns of mortar projectiles and three-dimensional plastic model of subtle object considering the temporal nature of the changes in the conditions of heat exchange, and various kinds of texture of soil surface and the depth of the object. Furthermore, it is shown that the inclusion of a specific internal content into a subtle object makes no significant effect on the temperature of the surface of the soil above it.

The mentioned papers suggest the need for further refinement of models of preferential consideration for the three-layer model (soil-object-soil), and the need for a detailed account of the natural heat exchange conditions. However, the proposed models have serious drawbacks, − they are either stationary or linear and are applied in the case of passive thermal location of subtle objects. At that, these papers do not put the inverse coefficient problem of estimating the subtle objects parameters on the dynamics of temperature contrasts that do not allow the consideration of problem of detection by measurements data of thermal parameters, both the of the object and the background, which are more informative than the value ofthermal contrasts.

Inverse heat conductivity problem can be solved by existing packages for thermodynamic modeling based on the finite difference method, elements, volumes, in particular COMSOL Multiphysics, ThermoAnalitics. The closest mathematical modelling package, based on the theoretical foundations of the radiation thermal physics, to the problem under consideration is the program RadThermIR (Pratmarty D, 2011).

However, its application does not yield the desired spatial distributions of thermal parameters - thermal tomograms in near real time. This very time limit for getting the solution of the inverse heat conductivity problem based on the construction of optimization problems, is a new requirement in the technology of infrared images reduction, remote sensing of Earth, detection of subtle objects in the optical wavelength range, diagnosing the state of pipeline transportation with UAVs, search and detection of hidden defects during thermal nondestructive control.

One of the ways to resolve the contradiction between the need to provide information on the spatial distribution of inhomogeneous isotropic media in the course of solving the problems of remote sensing in the infrared wavelength range and thermal nondestructive control to detect subtle objects in the structure of the environment, and the lack of models and methods enabling to receive real-time the display of thermal tomograms considering the thermal processes accompanying operation of subtle objects in the dynamics of heating and heat transfer, is the solution of the inverse heat conductivity problem with the use of special classes of functions and libraries of digital image processing called Open Source Computer Vision Library (OpenCV).

Therefore, to implement the solution of the inverse heat conductivity problem according to the remote measurement data of dynamic infrared images in real time, by reducing the need in computing resources, it is necessary to apply the algorithms providing acceptable accuracy of calculations with a minimum of computational operations, which is achieved by the following:

1. Infrared videoflow frame decomposition into subdomains.
2. Reduction of data information capacity for each subdomain.
3. Use of discrete models based on fast algorithm of iterative procedures.
4. Implementation of measurement process equation based on the method of comparison with a reference measurement value.

Procedures for decomposition of infrared videoflow frame on subdomains and decreasing of data information capacity in OpenCV are not standard, and their actual implementation depends on IDE (Integrated Development Environment) platform.

Construction of mathematical models based on fast algorithms requires consideration of two strategies: construction of discrete models most accurately reflecting the process of remote measurement of thermophysical parameters of an inhomogeneous isotropic medium and use of simplified analytical solutions with corrected output data using calibration function.

As a result of the optimization of parametric problem within the infrared image raster, it is possible receive distributions of estimated values of thermal conductivity and thermal diffusivity of the investigated isotropic material within the heating depth –thermal tomogram (Ishchuk et al., 2014 Part 1).

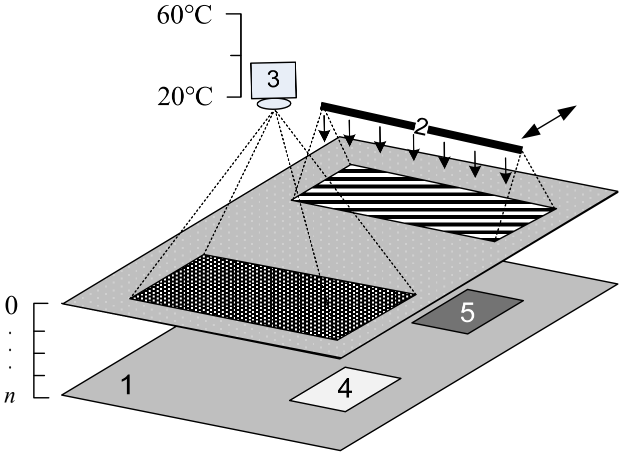


Figure 1. Scheme for obtaining cuboids of infrared images

The detailed scheme of the experiment is provided in a range of papers (López et al., 2014; Maldague, 1993; Štarman, 2008; Vavilov 2012).

We shall consider a practical example of the numerical solution of cuboids of infrared images reduction problem belonging to the class of computational thermal physic problems, which general formulation is given in the paper by (Ishchuk et al., 2014, Part 1):

$$A_{\xi}^{-1}\left(\mathbf{T}_{\mathrm{r}}\right)=\mathbf{f}\ , \tag{1}$$

where $\mathbf{T}_{\mathrm{r}}$ – is cuboid of infrared images obtained using an imaging infrared detector; $\mathbf{f}$ – is thermal tomogram (spatial distribution of thermal physic parameters of isotropic medium according to the implemented grid function);

$A_{\xi}^{-1}$ is $\xi$-parameter regularized inverse operator.

The solution for the cuboid of infrared images problem shall be represented in the form of the algorithm:

Step is the matrix of reference anisotropic material radiation temperatures values measured by the imaging infrared detector.

The solution for the cuboid of infrared images problem shall be represented in the form of the algorithm:

**STEP 1**. Formulation of the direct thermal conductivity problem describing thermal propagation in an anisotropic medium:

$$C\frac{\partial T}{\partial \tau} = \mathrm{div}(\lambda_1 \ \mathrm{grad}T) \ , \tag{2}$$

where $C = \rho \cdot c$; $\rho$ – is density; $c$ – is thermal capacity; $\lambda_1$ - is thermal conductivity; $T$ is the excess temperature; with boundary conditions of I and III nature.

$$-\lambda_1 \frac{\partial T_1}{\partial x}\Big|_{x=-0} - \alpha T_{\text{п}} = -q(\tau), \tag{3}$$

where $T_{\text{п}}$ is medium surface temperature; $\alpha$ is thermal transfer coefficient; $q$ is thermal flow density, $\tau$ – time.

Development of a mathematical model that adequately reflects the process of heat transmission in an anisotropic medium (MMA) based on (2), (3) shall be made using a one-dimensional differential equation of thermal conductivity based on assumptions $\partial C/\partial x \equiv 0$, represented as the difference approximation (Ishchuk et al., 2014 Part 1):

$$\frac{T^{k+1} - T^{k}}{\Delta \tau} = \sum_{i=1}^{3} \Lambda_{ii}(\eta T^{k+1} + (1-\eta)T^{k}), \tag{4}$$

where $\Lambda_{ii} T_n = a_1 \cdot \frac{T_{n+1} - 2T_n + T_{n-1}}{\Delta x^2}$; $\Lambda_{ii}$ is the difference operator; $\eta$ is weight coefficient, $\eta = 0$ (explicit scheme), $\eta \neq 0$ (implicit scheme, Crank-Nicolson scheme); $T_n^k$ is grid function; $n$ is spatial reference number; $k$ is time reference number.

For boundary conditions (3) approximation, the following expression shall be used (Ishchuk et al., 2014 Part 1):

$$-\lambda_1\left[\frac{T_n^k - T_{n+1}^k}{2}\right]\frac{T_n^k - T_{n+1}^k}{\Delta x} - \alpha[T_n^k]T_n^k = -q[k\Delta\tau] + \frac{\lambda_1[T_n^k]\Delta x}{2a_1[T_n^k]}\frac{T_n^{k+1} - T_{n+1}^k}{\Delta \tau}, \tag{5}$$

where

$$q(\tau) = \begin{cases} \left[1 - \exp\left(-\dfrac{\tau}{\beta_1}\right)\right]E, & \tau \le \tau^*; \\ \exp\left(-\dfrac{\tau - \tau^*}{\beta_2}\right)E, & \tau > \tau^*; \end{cases} \tag{6}$$

$\beta_1$, $\beta_2$ are the relaxation parameters of thermal flow at heating and cooling stage respectively; $E$ – is radiant emittance of the infrared emitter; $\tau^*$ is the time of thermal influence. Let the solution of the problem have the form of $T_1[\mathbf{\Psi}]$, where $\mathbf{\Psi}$ is MMA parameters vector.

**STEP 2**. Numerical evaluation of the spatial distribution of thermal flow falling on the surface of an anisotropic medium (set of points of an infrared image formed by the imaging infrared detector - $\mathbf{G}_0$), obtained by solving the optimization problem, minimizing offset $J$ between the data of remotely measured thermodynamic temperature values and values calculated on the basis of a mathematical MMA model using reference material with known thermal physic parameters at each point in the infrared image $\mathbf{G}$. Thus, the inverse problem in extremal formulation can be reduced to the minimization of the offset temperatures in the Euclidean metric:

$$\left\{ \underset{\mathbf{G}_0}{\mathbf{J}_{\mathrm{MMA}}}[\mathbf{q}] = \left\| \mathbf{T}_1[\mathbf{\Psi}:\mathbf{q}] - \tilde{\mathbf{T}}^{\text{Э}} \right\|^2 \right\} \to \min_{\mathbf{q}}, \tag{7}$$

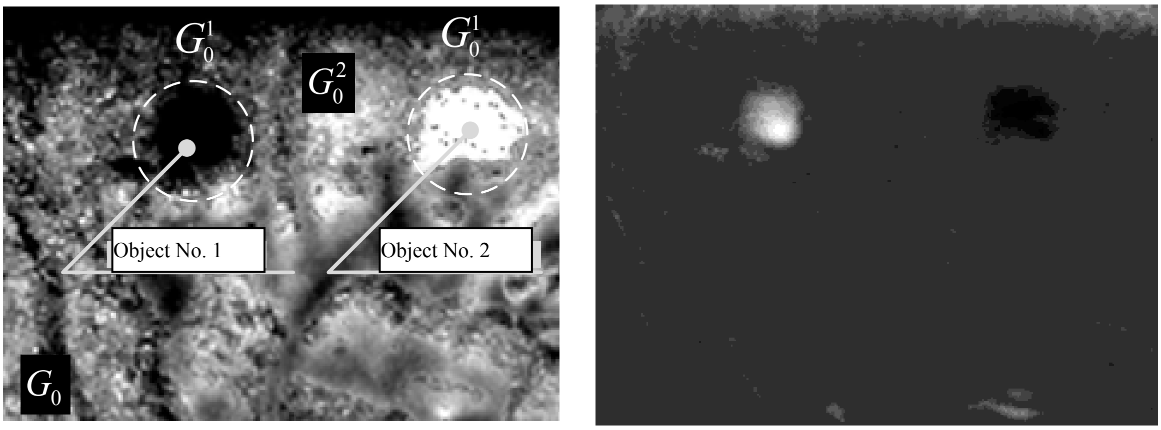
where $\mathbf{J}_{\mathrm{MMA}}$ is the matrix of offset temperature values using MMA; $\mathbf{q}$ is the matrix of thermal flow density values (thermal flow is taken from the infrared heat source); $\tilde{\mathbf{T}}^{э}$ is the matrix of reference anisotropic material radiation temperatures values measured by the imaging infrared detector.

**STEP 3**. Solution of the inverse thermal conductivity problem (ITCP) on the basis of the MMA for the evaluation of thermal and temperature conductivity values for anisotropic (researched) medium, at each point of the spatial resolution of the imaging infrared detector based on the estimated thermal flow density value $\hat{\mathbf{q}}$ Similarly, (7), numerical evaluation of thermal physic parameters of the upper layer of an anisotropic medium is made by minimizing the offset temperatures within the specified limits $a_{\min}<a_1<a_{\max}$, $\lambda_{\min}<\lambda_1<\lambda_{\max}$ :

$$\left\{ \underset{\mathbf{G}_0}{\mathbf{J}_{\mathrm{MMA}}}[\mathbf{f}_1] = \left\| \mathbf{T}[\mathbf{\Psi}:\mathbf{f}_1] - \tilde{\mathbf{T}} \right\|^2 \right\} \to \min_{\mathbf{f}_1}; \tag{8}$$

where $\mathbf{f}_1 = [a_1, \lambda_1]$; $\tilde{\mathbf{T}}$ is the matrix of radiation temperatures values of the researched anisotropic material measured by the imaging infrared detector. The result of thermal physic parameters recovery $\mathbf{f}_1$ by solving the extremal problem (8) using the method of coordinate-wise descent for an isotropic medium $a_1$=9·10$^{-7}$ м$^2$·с$^{-1}$, $\lambda_1$=0,9 Вт·м$^{-1}$·К$^{-1}$ where thermal insulation (object No. 1) and super thermal conducting materials (object No. 2) are located at a depth of 8 mm (presented in Figure 2).

At the locations of the buried objects $G_0^1 \subset G_0$, the images demonstrate that the condition of $J_{\mathrm{MMA}} < J_{\mathrm{lim}}$ is not met, where $J_{\mathrm{lim}}$ is the maximum value of the offset reflecting the compliance of MMA with the considered physic process; $G_0 \ldots G_n \subset G$ witnessing the need to use a mathematical model taking into account the multilayer structure of the medium, and therefore its isotropy.



a) thermal conductivity $\hat{\boldsymbol{\lambda}}_1$ b) temperature conductivity $\hat{\mathbf{a}}_1$

Figure 2. Spatial distribution of the evaluated values of thermal physic parameters $\hat{\mathbf{f}}_1$

**STEP 4.** The statement of the direct thermal conductivity problem and development of a mathematical model describing heat transmission in an isotropic medium (MMI), in accordance with (2), (3) and taking into account the conjugation conditions

$$\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{\mu_i} = \lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{\mu_i}; \tag{9}$$

$$T_1\big|_{\mu_i} = T_2\big|_{\mu_i},$$

where $\mu_i$ are the reference numbers of a spatial grid, which correspond to the conjugation boundaries of anisotropic media, where $i$ = 1.2.

Approximation of boundary conditions (9) by a difference scheme

$$T_{\mu_i}^{k} = \frac{\lambda_2}{\lambda_1 + \lambda_2} T_{\mu_i - 1}^{k} + \frac{\lambda_1}{\lambda_1 + \lambda_2} T_{\mu_i + 1}^{k} . \tag{10}$$

The numerical solution of this problem can be represented in the form of $T_2[\mathbf{\Psi}]$.

**STEP 5.** Solutions in the field of $G_0^1$ ITCP for the evaluation of thermal physic parameters of the buried object and its depth of burial:

$$\left\{ \mathbf{J}_{\underset{G_0^1}{\text{ММИ}}} \left[ \mathbf{f}_2 \right] = \left\| \mathbf{T}_2 \left[ \mathbf{\Psi} : \mathbf{f}_2 \right] - \tilde{\mathbf{T}} \right\|^2 \right\} \to \min_{\mathbf{f}_2}; \tag{11}$$

Thus, by solving the problem (7) based on the steepest descent method, it is possible to matrix of estimated values of the heat flow from the infrared heat source:

$$\hat{\mathbf{q}} = \begin{bmatrix} \hat{q}_{11} & \cdots & \hat{q}_{1n} \\ \cdots & \cdots & \cdots \\ \hat{q}_{m1} & \cdots & \hat{q}_{mn} \end{bmatrix}, \tag{12}$$

where $m \times n$ – is infrared image raster.

Solving the problem (8) and (11) by the method of Nelder-Mead, it is possible to receive distributions of estimated values of thermal conductivity and thermal diffusivity of the investigated isotropic material within the heating depth:

$$\hat{\boldsymbol{\lambda}} = \begin{bmatrix} \hat{\lambda}_{11} & \cdots & \hat{\lambda}_{1n} \\ \cdots & \cdots & \cdots \\ \hat{\lambda}_{m1} & \cdots & \hat{\lambda}_{mn} \end{bmatrix}, \quad \hat{\mathbf{a}} = \begin{bmatrix} \hat{a}_{11} & \cdots & \hat{a}_{1n} \\ \cdots & \cdots & \cdots \\ \hat{a}_{m1} & \cdots & \hat{a}_{mn} \end{bmatrix}. \tag{13}$$

Laboratory version of the device for the measurement and evaluation of thermal parameters of materials, implementing the proposed algorithm in the course of remote measurements, is presented in Figure 3.

Figure 3. Device for remote measurement of thermal parameters of isotropic materials

The device includes the following structural elements:

1. Infrared radiator heating the surface of the isotropic material with predetermined power and heating time.
2. Measuring thermal imager which allows surveying and formation of cuboids of infrared images of material surface with subsequent transfer to a storage device via USB-interface.
3. Unified framework and platform ensuring mounting of wheels system components, radiator, thermal imager, controllers system for motor control.

4. Automated control system, ensuring the implementation of measurement of thermal and physical parameters for isotropic materials.

Special software module implementing the solution of the problem of cuboids of infrared images reduction (1) and images of thermal tomograms.

## 4. Results

Solution of the problem of cuboids of infrared images reduction is represented in the form of heat tomogram mapping spatial distribution of thermal conductivity of isotropic medium over warming, depth (Figure 3). Analysis of the identified values of thermal conductivity over the area $G_0^2$ (76,800 values) demonstrated that the mathematical expectation of thermal conductivity was 0.892 $W \cdot m^{-1} \cdot K^{-1}$, and the standard deviation did not exceed 0.033 $W \cdot m^{-1} \cdot K^{-1}$, which allows the use of developed mathematical model to assess the heat parameters of the material by remote measurement of thermal tomograms on their surface.

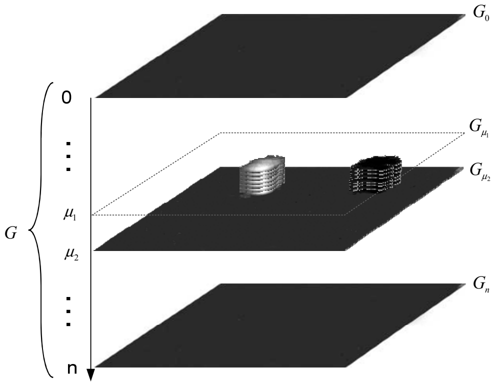


Figure 3. Spatial distribution of thermal conductivity of an isotropic medium over warming depth

Foreign objects $G_0^1$ are reliably distinguished in the area, at that, judging by the identified mean values of thermal conductivity (object No. 1 - 0.03 $W \cdot m^{-1} \cdot K^{-1}$, object No. 2 - 36.8 $W \cdot m^{-1} \cdot K^{-1}$) they can be definitely classified as heat insulators and heat conductors, respectively.

## 5. Conclusions

Thus, one of the universal methods of research of heat transfer processes in isotropic media is the use of numerical simulations based on the theory of difference schemes for finding an approximate solution for the problem by means of modern computer technologies and informatics. Solution of the parabolic equation using the Crank-Nicholson scheme and consideration of the multi-layer structure of the buried object can improve the adequacy of the mathematical model. This solution allows obtaining images of the thermal tomograms, in which each element displays the value of heat or thermal conductivity and depth-gram images in which each element displays the depth value of the layer in the multilayer structure of the anisotropic material. The algorithm for cuboids of infrared images reduction enables carrying out the comprehensive numerical study of thermal physic processes, exposing them to numerical experiments, by analyzing a variety of situations, and obtaining information about the buried object. This method is the basis for a more efficient solution of problems on detection, recognition, and identification of quasi-stationary objects in the infrared wavelength range, including camouflaged on the Earth's surface, using UAV's, equipped with thermal vision monitoring systems, which greatly expands the possibilities of the known methods (López et al., 2014; Štarman et al., 2008; Swiderski, 2012).

## Acknowledgements

The work was financially supported by the Russian Ministry of Education (Contract no.14.578.21.0021).

## References

Broberg, P., & Runnemalm, A. (2012). *Detection of Surface Cracks in Welds using Active Thermography* 18th World Conference on Nondestructive Testing, 16-20 April, Durban, South Africa.

Davis, A. J., & Venkatraman, B. (2012). *A Heat Transfer Methodology to Monitor Flow Accelerated Internal Corrosion in Steam Pipes*. 18th World Conference on Nondestructive Testing, 16-20 April, Durban, South Africa.

Hartless, P. C. M., & Whalley, D. C. (1991). *Automated Thermographic Inspection of Surface Mount Solder Joints*. *Automotive Electronics,8*(28-31), 178-181.

Ishchuk, I. N., & Parfiriev, A. V. (2014). *The Reconstruction of a Cuboid of Infrared Images to Detect Hidden Objects. Part 1. A Solution Based on the Coefficient Inverse Problem of Heat Conduction. Measurement Techniques, 56*(10), 1162-1166. http://dx.doi.org/10.1007/s11018-014-0349-8

Ishchuk, I. N., & Parfiriev, A. V. (2014). The Reconstruction of a Cuboid of Infrared Images to Detect Hidden Objects. Part 2. *A Method and Apparatus for Remote Measurements of the Thermal Parameters of Isotropic Materials*. *Measurement Techniques, 57*(1), 74-78. http://dx.doi.org/10.1007/s11018-014-0409-0

Ishchuk, I. N., Karpov, I. G., & Fesenko, A. I. (2009). *The detection of hidden subsurface objects in the infrared wavelength band by identifying their thermal properties*. *Measurement Techniques, 52*(4), 388-393. http://dx.doi.org/10.1007/s11018-009-9282-7

López, F., Ibarra-Castanedo, C., Nicolau, V. P., & Maldague, X. (2014). Comparative study of Thermographic signal reconstruction and partial least-squares thermography for detection and evaluation of subsurface defects. *12th International Conference on Quantitative Infrared Thermography, Bordeaux, France.*

Maldague, X. P. V. (1993). *Nondestructive Evaluation of Materials by Infrared Thermography:* London: Springer: ISBN-13:978-1-4471-1997-5, 207. http://dx.doi.org/10.1007/978-1-4471-1995-1

Pratmarty, D., & Cathala, T. (2011). *Software coupling between RadThermIR and SE-WORKBENCH*. Retrieved from http://ebookbrowse.com/radtherm-oktal-se-itbm-s2011-paper-pdf-d443040793

Ringermacher, H. I., Howard, D. R. B., & Knight, D. R. (2012). *Thermal Imaging NDT at General Electric*. 18th World Conference on Nondestructive Testing, 16-20 April, Durban, South Africa.

Štarman, S., & Matz, V. (2008). *Automated System for Crack Detection Using Infrared Thermographic Testing*. 17th World Conference on Nondestructive Testing, 25-28 Oct, Shanghai, China.

Swiderski, W. (2012). *Microwave Radiation in Thermal Detection of Buried Objects - Modeling and Experiments* 18th World Conference on Nondestructive Testing, 16-20 April, Durban, South Africa.

Vavilov, V. (2012). *Modelling Thermal NDT Problems* 18th World Conference on Nondestructive Testing, 16-20 April, Durban, South Africa.

Winter, E. M. (2004). *Joint multisensor exploitation for mine detection* Proc, of the SPIE: Detection and Remediation Technologies for Mines and Minelike Targets IX, Bellingham, 5415, 1094–1104.

## Copyrights