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INFORMATION SUPPORT OF FINDING A SOLUTION THE PROBLEM OF HIDDEN OBJECTS

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ABSTRACT

We developed a new approach to heat transfer processes, based on the formulation and solution of a new class of inverse heat conduction problems, which differs from previously known methods in the use of qualitative information. The authors propose an approach based on the relevant account of a priori information about the unknown quantities, which can be represented by the application of the theory of fuzzy sets, in particular, by the use of LR-type fuzzy numbers or fuzzy functions. The solution of the inverse heat conduction problem by infrared images obtained with the UAV allowed detecting objects by similar thermal parameters; image segmentation of thermal tomogram allowed identifying objects invisible on the original IR images.

Keywords: *Inverse Heat Conduction Problem; IR Image; Thermal Physical Parameters; Thermal Tomogram*

1. INTRODUCTION

In recent years, the theory and practice of research into heat exchange processes, design and simulation of thermal conditions of technical systems have seen a rapid development of approaches based on the formulation and solution of a new class of inverse heat conduction problems, which are significantly different from previously known methods as they use qualitative information formalized by fuzzy measures, possibility measures, etc. [1-6]. This leads to the necessity of improving the existing methods and developing new ones to solve inverse heat conduction problems, as well as develop methods of processing the information obtained as a result of their solutions [4-10].

A special meaning these methods obtain under experimental study of substandard thermal processes with the use of thermal imaging devices working in IR range by way of distance determination of thermal physical properties of materials ranking to different classes and being both isotropic and anisotropic.

A special meaning under distance determination of thermal physical properties obtains a process of making the space-time distribution of radiation temperature (cuboid of infrared images). The method of the space-time distribution of radiation temperatures is considered in papers [9-11] and provided the positive results obtainment in solving a set of applied problems.

The problems of determining thermal properties of materials are particularly important for the purpose of constructing and analyzing infrared images; solutions of these problems allow us to classify the objects to be identified.

2. METHOD

We consider the process of unsteady heat transfer in a rectangular region of an anisotropic material regarding thermal conductivity. If we assume that the solution is unique and consider the conditions of the first kind as the boundary conditions, the mathematical model of the process has the form of the following boundary value problem:

$$C(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_{11}(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{22}(T)\frac{\partial T}{\partial y}\right) + 2\frac{\partial}{\partial x}\left(\lambda_{12}(T)\frac{\partial T}{\partial y}\right) + S(x,y,\tau), \quad (1)$$

$$x \in [0,a], y \in [0,b], \tau \in [0,\tau_m],$$

$$T(x,y,0) = \varphi_0(x,y), \quad (2)$$

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$$T(x_\Gamma, y_\Gamma, \tau) = \varphi_\Gamma(x_\Gamma, y_\Gamma, \tau), \quad (3)$$
$$x_\Gamma = \{0; a\}, y_\Gamma = \{0; b\}, \tau \in [0, \tau_m],$$
$$C(T) = c(T)\rho(T),$$

where $c(T)$ – heat capacity, $\rho(T)$ – density, $\varphi_0(x, y)$ и $\varphi_\Gamma(x_\Gamma, y_\Gamma, \tau)$ are known functions.

We consider the problem of function recovery $\lambda_{11}(T)$, $\lambda_{22}(T)$, $\lambda_{12}(T)$ and $C(T)$ on the basis of information on the instantaneous values of temperatures in certain n points of the rectangular area $G = [0;a]\times[0;b]$ ($T(x_i, y_i, \tau) = f(x_i, y_i, \tau)$, $i = 1,2,\dots,n$) and known functions $S(x,y,\tau)$, $\varphi_0(x, y)$, $\varphi_\Gamma(x_\Gamma, y_\Gamma, \tau)$.

Functions to be identified $\lambda_{11}(T)$, $\lambda_{22}(T)$, $\lambda_{12}(T)$ and $C(T)$ are rewritten in parametric form:

$$\lambda_{11}(T) = \sum_{k=1}^{m+3} \lambda_{11}^{(k)} L_k(T),$$
$$\lambda_{22}(T) = \sum_{k=1}^{m+3} \lambda_{22}^{(k)} L_k(T),$$
$$\lambda_{12}(T) = \sum_{k=1}^{m+3} \lambda_{12}^{(k)} L_k(T),$$
$$C(T) = \sum_{k=1}^{m+3} C^{(k)} L_k(T),$$

where $L_k(T)$ is the sequence of Lagrange interpolation polynomials; $T\in[T_{\min},T_{\max}]$; m is the number of sections of the domain partition of the sought-for functions in spline approximation;

$$\lambda_{11} = \left(\lambda_{11}^{(k)}, k = 1,2, \dots, (m+3)\right),$$
$$\lambda_{22} = \left(\lambda_{22}^{(k)}, k = 1,2, \dots, (m+3)\right),$$
$$\lambda_{12} = \left(\lambda_{12}^{(k)}, k = 1,2, \dots, (m+3)\right),$$
$$\mathrm{C} = \left(C^{(k)}, k = 1,2, \dots, (m+3)\right)$$

are vectors of interpolating polynomials parameters.

Will consistently clarify the solution making corrections to vector parameters of interpolation polynomials in conditions of decreasing functional J, which has the form:

$$J = \frac{1}{2}\sum_{i=1}^{n} \int_0^{\tau_m} \left(T(x_i, y_i, \tau) - f(x_i, y_i, \tau)\right)^2 d\tau. \quad (4)$$

Point out that solving the inverse problem with the functional (4) doesn't possess uniqueness property. The way out from this situation is possible in the case of using the transcendent information about values needed to be determined, in particular about quality character of their changing on temperature interval of interest, which may be formalized on the base of using the methods of fuzzy sets theory including the fuzzy numbers of LR-type or fuzzy function [1-4].

We form the Lagrange functional Φ.

$$\begin{aligned}\Phi &= \frac{1}{2}\sum_{i=1}^{n}\int_0^{\tau_m} (T(x_i, y_i, \tau) - f(x_i, y_i, \tau))^2 d\tau \\ &+ \sum_{i=1}^{n}\int_0^{\tau_m} \psi(x_i, y_i, \tau)\Bigg[\frac{\partial}{\partial x}\left(\lambda_{11}(T)\frac{\partial T}{\partial x}\right)_{x=x_i, y=y} \\ &+ \frac{\partial}{\partial y}\left(\lambda_{22}(T)\frac{\partial T}{\partial y}\right)_{x=x_i, y=y_i} + 2\frac{\partial}{\partial x}\left(\lambda_{12}(T)\frac{\partial T}{\partial y}\right. \\ &+ S(x, y, \tau) - \left(C(T)\frac{\partial T}{\partial \tau}\right)_{x=x_i, y=y_i}\Bigg] d\tau \\ &+ \sum_{i=1}^{n} \gamma(x_i, y_i)[T(x_i, y_i, 0) - T_0(x_i, y_i)]\end{aligned} \quad (5)$$

To obtain the formula of the objective function gradient we transform the expression$\Delta\Phi$.

We select the linear part of the functional (5) which has the form:

$$\sum_{k=1}^{m+3} J'\left(\lambda_{11}^{(k)}\right)\cdot\Delta\lambda_{11}^{(k)} + \sum_{k=1}^{m+3} J'\left(\lambda_{22}^{(k)}\right)\cdot\Delta\lambda_{22}^{(k)} + \sum_{k=1}^{m+3} J'\left(\lambda_{12}^{(k)}\right)\cdot\Delta\lambda_{12}^{(k)} + \sum_{k=1}^{m+3} J'\left(C^{(k)}\right)\cdot\Delta C^{(k)},$$

and corresponds to the gradient of the functional in the considered problem.

$$\begin{aligned}\Delta\Phi = &\sum_{k=1}^{m+3}(J'\left(\lambda_{11}^{(k)}\right)\cdot\Delta\lambda_{11}^{(k)} + J'\left(\lambda_{22}^{(k)}\right) \\ &\cdot\Delta\lambda_{22}^{(k)} + J'\left(\lambda_{12}^{(k)}\right)\cdot\Delta\lambda_{12}^{(k)} \\ &+ J'\left(C^{(k)}\right)\cdot\Delta C^{(k)}) \\ &+ \sum_{i=1}^{n}\int_0^{\tau_m} \psi(x_i, y_i, \tau) \\ &\cdot\{\frac{\partial}{\partial x}\left(\lambda_{11}(T)\frac{\partial\theta}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\lambda_{22}(T)\frac{\partial\theta}{\partial y}\right) \\ &+ 2\frac{\partial}{\partial x}\left(\lambda_{12}(T)\frac{\partial\theta}{\partial y}\right) + \\ &+\theta\cdot[\frac{d\lambda_{11}}{dT}\frac{\partial^2 T}{\partial x^2} + \frac{d^2\lambda_{11}}{\partial T^2}\left(\frac{\partial T}{\partial x}\right)^2 + \frac{d\lambda_{22}}{dT}\frac{\partial^2 T}{\partial y^2} \\ &+ \frac{d^2\lambda_{22}}{\partial T^2}\left(\frac{\partial T}{\partial y}\right)^2 \\ &+ 2\frac{d\lambda_{12}}{dT}\frac{\partial^2 T}{\partial x\partial y} \\ &+ 2\frac{d^2 T}{dT^2}\frac{\partial T}{\partial x}\frac{\partial T}{\partial y} - \frac{dC}{dT}\frac{\partial\theta}{\partial\tau}] \\ &+ \\ &+\frac{d\lambda_{11}}{dT}\frac{\partial T}{\partial x}\frac{\partial\theta}{\partial x} + \frac{d\lambda_{22}}{dT}\frac{\partial T}{\partial y}\frac{\partial\theta}{\partial y} + 2\frac{d\lambda_{12}}{dT}\frac{\partial T}{\partial y}\frac{\partial\theta}{\partial x} \\ &- C(T)\frac{\partial\theta}{\partial\tau}\}\cdot d\tau +\end{aligned} \quad (6)$$

$$+\sum_{k=1}^{m+3}\Delta\lambda_{11}^{(k)}\cdot(\sum_{i=1}^{n}\int_{0}^{\tau_m}\psi(x_i,y_i,\tau)\cdot\left[\frac{\partial^2 T}{\partial x^2}L_k(T)+\left(\frac{\partial T}{\partial x}\right)^2\frac{dL_k}{dT}\right]d\tau)+$$
$$+\sum_{k=1}^{m+3}\Delta\lambda_{22}^{(k)}\cdot(\sum_{i=1}^{n}\int_{0}^{\tau_m}\psi(x_i,y_i,\tau)\cdot\left[\frac{\partial^2 T}{\partial y^2}L_k(T)+\left(\frac{\partial T}{\partial y}\right)^2\frac{dL_k}{dT}\right]d\tau)+$$
$$+2\cdot\sum_{k=1}^{m+3}\Delta\lambda_{12}^{(k)}\cdot(\sum_{i=1}^{n}\int_{0}^{\tau_m}\psi(x_i,y_i,\tau)\cdot\left[\frac{\partial^2 T}{\partial x\partial y}B_k(T)+\frac{\partial T}{\partial x}\frac{\partial T}{\partial y}\frac{dL_k(T)}{dT}\right]d\tau)+$$
$$+\sum_{k=1}^{m+3}\Delta C^{(k)}\cdot(\sum_{i=1}^{n}\int_{0}^{\tau_m}\psi(x_i,y_i,\tau)\cdot\frac{\partial T}{\partial \tau}L_k(T)d\tau).$$

The inverse heat conduction problem can be solved by existing thermodynamic modeling packages based on the finite difference method, the elements, the volume, in particular, COMSOL Multiphysics, ThermoAnalitics. The closest to the task (5) package of mathematical modeling, based on the theoretical foundations of thermal radiation physics, is the RadThermIR program [11].

However, the use of ready-made software application, enable to solve common tasks properly, as a rule, in the case of its use for new non-standard tasks in real time does not yield the desired result, which involves on the one hand the efficiency and on the other hand the desired spatial distributions of thermal parameters obtaining - thermal tomograms. It is an efficiency requirement of obtaining the task solution (1) - (3), based on the construction of the optimization problem (5), is a new requirement in the technology of detection and identification of stealth objects, in monitoring the state of pipeline transport objects from unmanned aerial vehicles, search and detection of hidden defects during the thermal non-destructive control.

Despite the fact that for digital image processing there is a library of Open Source Computer Vision Library (Open CV) which contains a considerable range of functions and classes, but in solving inverse problems and building thermal tomograms it is required the additional use of contour and fractal analysis methods [4, 5]. That was the basis for the development of appropriate algorithms and software implementations, allowing in real-time mode to receive the thermal tomograms imaging taking cue from the thermal processes and the solution of coefficient inverse problem (5).

Thus, in order to ensure the efficiency of solving the inverse problem using the information in the form of infrared images it is needed to use effective, in terms of computational cost and accuracy, algorithms both for the solution of the problem and for processing the infrared image. Algorithms satisfying the requirements listed above, for the solution of task (5) are well known and are based on gradient search. The access of the efficiency while processing the infrared image is achieved by the use of:

1. Selection of specific areas on a single frame of infrared image by methods of contouring analysis.
2. Roughening of data for specific areas of informational capacity
3. Using a discrete analogue of task (1) - (3) and effective iterative algorithms to solve it.
4. Using effective gradient methods for solving the problem (1) - (4).

As a result of optimization problem solution (1) - (4) based on the processing of infrared images it is obtained the distribution of the estimated values of thermal conductivity and thermal diffusivity of tested material [12, 13]:

$$\lambda=\begin{bmatrix}\lambda_{11} & \dots & \lambda_{1n}\\ \dots & \dots & \dots\\ \lambda_{m1} & \dots & \lambda_{mn}\end{bmatrix}. \qquad (7)$$

3. RESULTS

Let us consider a model situation of obtaining dynamic infrared images presented in Fig. 1, where 1 is isotropic medium; 2 is a source of infrared heating performing uniform heating of the surface of an isotropic medium (quartz sand) for 60 sec; 3 is thermal imaging receiver continuously recording thermograms of the medium surface for 180 sec; 4 is a superthermal material (aluminum); 5 is an insulating material (foamed plastic).

The best possible IR image of the anisotropic medium surface is shown in Fig. 2.

Fig. 3 shows the solution of the problem (5) of identification of the numerical value of the thermal conductivity of quartz sand; Fig.4 shows the obtained numerical value of the functional (4) in the form of spatial distribution.

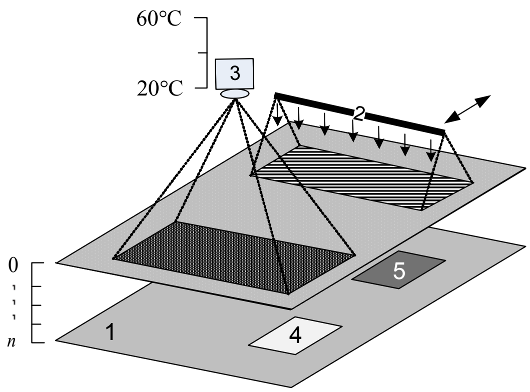

Fig. 1 - The scheme for obtaining dynamic IR images

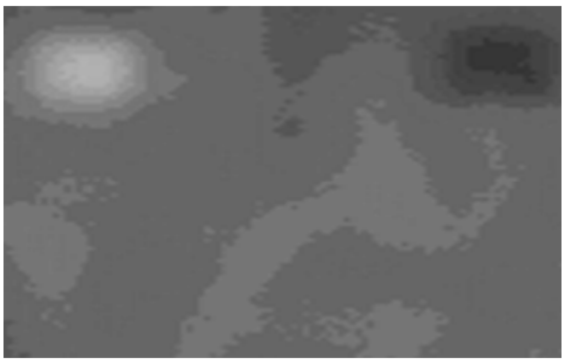

Fig. 2 - The thermogram of the anisotropic material surface at the time point of 100 seconds after starting the test with a duration of heat exposure of 60 sec

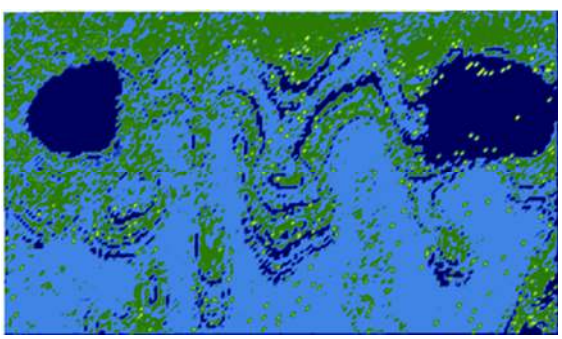

Fig. 3 – The thermal tomogram on thermal conductivity

The analysis of the spatial distributions of the identifiable parameters showed that in the locations of irregularities 4 and 5, according to the scheme of the experiment (Fig. 1), the discrepancy has maximum values, and the image of thermal tomogram showed their exact location and geometric shape.

Fig.5 shows the solution of the problem of λ (T) function recovery by the depth of heating the inhomogeneous medium on the basis of information about the instantaneous values of the temperature distribution on its surface in G_0 rectangular region. The non-uniform inclusions (objects 4 and 5, Fig. 1) are shown as spatial distributions of thermal conductivity on $G_{\mu1}\ldots G_{\mu2}$. layers.

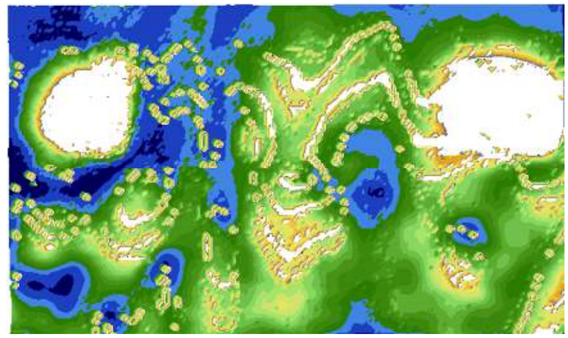

Fig. 4 - Discrepancy

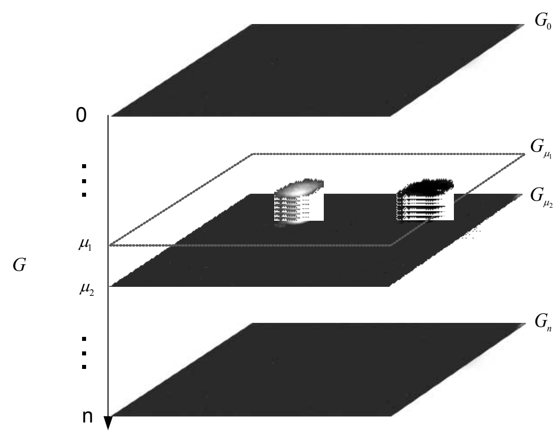

Fig. 5 – Changing of environment thermal conductivity in depth of heat

The solution of inverse problem by using infrared images obtained with UAV at night time when shooting the same plot of area every 10 minutes during an hour and a half is shown in Fig.6.

a)

b)

Fig. 6 Infrared Images Obtained From The UAV At A) 1.10 Am; B) 2.40 Am.

Buildings, a river, tree crowns and a car are visible in the infrared images. In turn, the result of solving the problem (5) for the four reference objects (tree crowns, roof slate, water, metal) made it possible to obtain thermal tomogram (Fig. 7), which shows the places of water accumulation, zones of forest plantations, soil, metal objects and residential buildings.

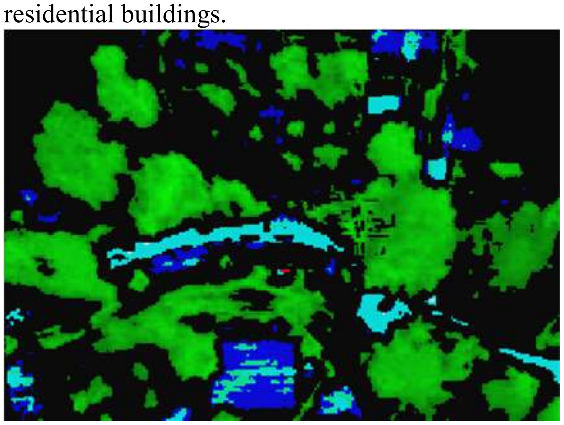

Fig. 7 - Thermal Tomogram Made By IR Images From Uavs

In addition, the use of segmentation algorithms for the thermal tomogram made it possible to identify objects on it with similar thermo-physical parameters (Fig. 8).

a)

b)

Fig. 8 - Segmentation Of Thermal Tomogram: A) The Object "Water"; B) The Object "Metal"

The analysis of Fig. 8a shows that there is some water on the roofs of buildings, and Fig. 8b shows the exact location of the metal pillars of the bridge across the river.

4. CONCLUSION

The solution of the inverse heat conduction problem by IR images taken from the UAVs allowed detecting objects by similar thermal parameters; the image segmentation of the thermal tomogram allowed identifying objects invisible on the original IR images. Thermal tomograms can be used to improve the efficiency of monitoring of the Earth's surface and evaluate the effectiveness of reducing the visibility of man-made objects or their disclosure.

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