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Cuboids of Infrared Images Reduction Obtained from Unmanned Aerial Vehicles

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Abstract

Currently, both in practice and in theory, there is an acute contradiction between the current state of scientific, technical, and engineering achievements in the field of aerospace monitoring and lack of sufficient volume of new knowledge (models and methods) about the peculiarities of thermal processes accompanying operation of hidden objects.

Removing this contradiction is substantially related to the solution of the problem on the solution of the actual scientific problem on developing thermal tomograms of the Earth's surface, based on the solution of the coefficient inverse problem, in order to find and discover the hidden objects during the monitoring of the Earth's surface using unmanned aerial vehicles (UAV).

The paper presents experimental data on the spatial distribution of thermal parameters of the objects. The paper reflects their effective thermal conductivity in the course of daily observations in the infrared wavelength range using unmanned aerial vehicles. The measurement results proved the possibility of obtaining a numerical evaluation of the visibility of objects through research of manifestations of thermal physic properties in the nature of the radiation of electromagnetic waves in the infrared range.

Keywords: monitoring of the Earth's surface, thermal physic parameters, cuboid of images, thermal tomogram

1. Introduction

At solving the problem of detection and recognition of objects located on the ground surface or buried in it by infrared images, the attention-calling sign is the difference in energetic brightness of the object and the background. These differences are commonly characterized by the concept of radiative thermal contrast, which for homogeneous objects and backgrounds is determined by the ratio of the differences in radiances of the object and the background to their sum.

The main parameters influencing the formation of the optical field of the scanned surface of the ground in the infrared wavelength range are: absolute temperatures, thermal emissivity coefficients, spectral and integral reflection coefficients, thermal and physical properties of the objects and the background. In addition, the variations of the atmospheric conditions (cloudiness, humidity, air temperature, pressure, wind speed), solar activity, time of the day and year, geographic coordinates, etc. also have their influence. Thus, energetic radiance, both of the object and the background, includes the contribution of the three components: reflected, absorbed (reradiated) and intrinsic (internal) energy.

Applying the Stefan-Boltzmann law for each of the component of energetic radiance of the object and the background, it is possible to determine their thermodynamic temperature. In practical calculations it is suggested that the emissivity and reflection in the infrared spectral operating range of the system are constant. Accordingly, the temperature of the object and the background is significantly affected by both the reflection coefficient determining the radiation temperature increase due to absorption of solar radiation, and the coefficient of thermal radiation directly determining their absolute temperature. It shall be noted that the absolute temperature of the object and the background is formed as a result of heat exchange processes: radiant process, convective process and heat transfer. In addition to the observation process is influenced by such processes as radiation attenuation by atmosphere, distortion of temperature fields in conditions of high soil moisture and forced convection, etc.

In connection with the above-said, to improve the information content of the infrared images, it is necessary to apply models and methods for automatic remotely measurement of optical and thermal parameters of materials, acting as evaluation of the visibility of objects in the infrared wavelength range.

Known thermal models of objects in the natural heat exchange conditions obtained depending on the material, shape and size of objects, heating conditions, soil type, topography, sunny weather properties, however, have a number of disadvantages - they are either stationary or linear and are applied in the case of passive heat locations of objects. At that, the analysis of information based on existing model concepts is a judgment about the discovery according to temperature contrasts, which reduces the effectiveness of the visibility assessment of objects in the infrared wavelength range on the background of soil.

One of the ways of increasing the effectiveness of the monitoring the Earth's surface in order to reveal hidden objects is the remote measurement of thermal physical parameters (TPP) of these objects with the use of optoelectronic systems, and unmanned aerial vehicles.

Optoelectronic systems of infrared wavelengths are characterized by the following indices (Maldague, 1993):

- minimum detectable temperature difference (thermal sensitivity), it is the minimum difference of the radiation temperatures of the object with specified size and background in which the object is detected;
- minimum resolvable temperature difference (temperature resolution), it is the minimum difference of the radiation temperatures of stroke azimuth mark bands with certain period and background, which strokes of the azimuth mark are allowed on the output image;
- angular resolution, it is the angular period of the azimuth mark with a certain difference in radiation temperature with the background, which strokes of the azimuth mark are allowed on the output image;
- elementary vision range;
- area capture bandwidth;
- the number of reproducible temperature gradations.

Thermal mode of the soil is determined by its complex optical, thermal and physical properties. The optical parameters of the soil depend significantly on the spectral composition of the radiant flux acting in the shortwave (solar radiation) and longwave (atmosphere thermal radiation) wavelengths.

Let us consider the average annual heat balance of the atmosphere and the Earth's surface. Self-radiation of the Earth consists of the two components: infrared and reflected radiance. Absorpbed solar radiation is balanced by the outgoing longwave radiation flux, together with the loss of explicit (surface cooling) and hidden (melting, evaporation) heat. At short intervals of time, these quantities are unbalanced, whereby the surface temperature changes dynamically. Changing of the direction of the total heat flow (from the Earth or to the Earth) leads to the fact that because of the differences of soil and sampled materials TPP, their surface experiences formation of temperature distribution perceived by OES and described energy characteristics.

The main reason for the consideration of the energy values is because of the high frequency vibrations and inertia of OES, it is practically impossible to measure instantaneous amplitude of the wave. So the simplest recorded values are those that depend on the stress squares, such as the volumetric density of energy radiation, flux density of energy radiation, and radiation power.

In general, the background signal is generated in the process of infrared waves passing through a medium affecting them as follows:

- ambient radiation reflected by the background changes the background temperature radiation value;
- atmosphere attenuates (reduces) the background radiation temperature value to the value depending on the transmission coefficient;
- turbulence and aerosol diffusion of the atmosphere blurs the edges of the image.

The most important generalized parameter of the atmosphere is its transmittance on the channel.

For statistical evaluations of the background signal, the two indicators are used: average background temperature value (radiation temperature value) and maximum spread of the background radiation temperatures. Analysis of experimental data on the statistics of thermal fluctuations of natural terrestrial backgrounds, as well as generalized dependence of the magnitude of fluctuations on the time of day and year shows that the fluctuations of the background radiation temperature follow the rule close to normal, and their maximum value depends on the type of background and weather conditions and do not exceed 3 degrees by Kelvin. During night time, the value of fluctuations in average is two times less than during the day at cloudy weather.

During the signal reception, OES moves in space, forming a trajectory signal by line or frame scanning. At providing shooting of still images of soil by OES (using an unmanned helicopter), area background signal is formed by frame scanning method of one and the same area section at a given time interval.

Wanted signal (abnormal background signal) is formed similarly to the background signal, reflecting in itself the information about the presence of an object in the soil structure.

Therefore, excluding the optical laws of radiation absorption and thermal physics of heat flow, it is not possible to explain fully the mechanism of radiation temperature formation at the soil surface and objects sampled by UAV, especially in terms of hydro-meteorological uncertainty.

Examining this process in the framework of radiation thermal physics, the formulations of the relevant boundary problems of heat exchange are undergoing significant changes.

First, the boundary condition of heat exchange on the ground surface changes. It shall consider the following factors: turbulent heat exchange, surface radiation and atmosphere counterradiation, heat loss by evaporation from the surface. In some cases a combination of boundary and volume absorption is possible.

Secondly, it is necessary to allocate a number of climate-determining parameters in the boundary conditions: average value of the solar radiation and mean temperature coefficient of the turbulent heat exchange.

Third, to the optical thermal and physical properties of materials shall cover the following: thermal and physical properties - thermal diffusivity and conductivity; optical properties - emissivity and reflection coefficient.

Image of the monitoring object in the spectral range of 8-14 microns may be obtained with sufficient practical accuracy on the basis of numerical simulation by solving a nonlinear boundary value problem of nonstationary heat conduction for bodies of complex shape.

2. Literature Review

Finding hidden objects by their signatures obtained using optoelectronic systems is not always effective, as it depends on external factors. One of the main factors is the weather. Thus, the paper (Swiderski W., P. and Hlosta et al., 2012) represents a research on the influence of moisture content and density of the soil, and the article (Lamorski et al., 2001) speaks about the influence of soil type (mineral, organic) on the efficiency of hidden objects detection.

However, the majority of well-known papers, as, for example, by (Swiderski, Hlosta, Miszczak, 2012; Vavilov, 2012; Pregowski et al., 2000) utilize simplified solution of the direct thermal conductivity problem. Thus, the article by (Swiderski, 2012) represents models for consideration of solid, liquid, and gaseous values of thermal capacity, but the heat and mass transfer problem is not considered at all. The authors, as it is seen from the papers (Štarman, 2008) and (Lamorski et al., 2001) reduce the solution of the thermography problem to the comparison of the experimentally obtained infrared signatures with the reference images.

Revealing the hidden objects based on the data of remote TPP measuring allows to get the evaluation of the visibility of the object by comparing the integral TPP values of the object and the background, which practically do not depend on external factors and time of the day (Ishchuk et al., 2014 Part 1, Part 2). However, these studies do not consider identification of a hidden object by analysing the signature of the hidden object under natural heat transfer.

3. Materials and Methods

Monitoring of the Earth's surface in the remote TPP measurement shall be based on the following initial data:

- geographical location data and characteristics of the object location area;
- average (integral) TPP values of the hidden object, means of reducing its visibility and masking environment;
- simulated situation;
- operational and physical characteristics of infrared monitoring means.

The procedures for the control provide heating of the control object under natural heat exchange in the daytime and the subsequent continuous or periodic measurement of the radiation temperatures at the surface of the object and of the background in the night, allowing formation of cuboids of infrared images. At the same time, there are limitations based on the measurement according to meteorological conditions, masking environment and time of the day.

In turn, use of unmanned aerial vehicles with an optoelectronic system placed can improve mobility and increase the area of the Earth's surface to be monitored in order to find hidden objects using their TPP.

Cuboids of infrared images can be formed in the two ways:

1. On a given altitude, an unmanned aerial vehicle performs registration of infrared images of the same site with a set interval.

2. Helicopter type unmanned aerial vehicles are used, which can fly at low altitude and hover over inconspicuous objects to conduct infrared shooting of the area.

Formed cuboids of infrared images are processed based on the method of thermal tomography conversion into heat tomograms. The last are used to solve the problem of estimating the probability of detection and recognition of objects to be monitored, and to develop their three-dimensional reconstruction.

Cuboids of infrared images reconstruction (reduction) problem has the following form (Ishchuk et al., 2014 Part 1, Part 2):

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

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

A_{ξ}^{-1} is parameter regularized ξ inverse operator, and conversion of thermal tomograms into heat tomograms according to offset temperatures:

$$\left\{\mathbf{J}\left[\mathbf{f}\right]=\left\|\mathbf{T}[\boldsymbol{\Psi}:\mathbf{f}]-\tilde{\mathbf{T}}\right\|^{2}\right\}\rightarrow\min_{\mathbf{f}}, \tag{2}$$

where $\mathbf{J}$ is the matrix of offset values; $\mathbf{T}[\boldsymbol{\Psi}]$ is the mathematical model (Ishchuk et al., 2014 Part 1); $\boldsymbol{\Psi}$ is the vector of mathematical model parameters; $\tilde{\mathbf{T}}$ is the matrix of radiation temperature values on the surface of objects to be monitored, measured by an optoelectronic system in infrared wavelengths.

Using a simplified mathematical model, represented by a vector of thermodynamic temperature values for n reference objects, can significantly reduce the computational resources, and solve the problem of classification. However, it requires the use of sets of materials with known TPP.

Let us consider the algorithm for solving the problem of infrared images reduction from UAVs.

STEP 1. Estimation of unknown parameters of the mathematical model $\tilde{\mathbf{T}}$ based on the use of n reference materials for which a UAV with a thermal receiver is placed stationarily above reference materials at a height determined by the lowest visible point or are moved at a constant speed.

Thermal imaging receiver measures the radiation temperature in one of the smallest measurement point in the centre of the surface area of each reference material entering the lens of the thermal imaging receiver.

Watching excessive temperatures measured by the thermal imaging receiver in the lowest measurement point is made at a time interval of .

Using data of the measured radiation temperature at the least visible point in space of the resolution of each reference materials, it is possible to solve the optimization problem (2), thereby obtaining the estimated values of the unknown parameters of the mathematical model for each reference material

STEP 2. Evaluation of thermal parameters at each point of object resolution space by means of monitoring by numerical solution of the direct heat conductivity problem:

Formulation of the direct problem of heat conductivity, describing the propagation of heat in the anisotropic medium:

$$C\frac{\partial T}{\partial\tau}=\mathrm{div}(\lambda\ \mathrm{grad}T)\ , \tag{3}$$

where $C=\rho\cdot c$; ρ – density; c – thermal capacity; λ – heat conductivity; T – excess temperature; τ – time with boundary values of II and III gender:

$$-\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=-0} - \alpha T_{\Pi} = -q(\tau)\,, \tag{4}$$

where $T_{п}$ – medium surface temperature; α – heat transition coefficient; q – heat flux density.

For getting a simplified solution of the problem (2), the mathematical model of the solution (3), (4) $-\mathbf{T}[\mathbf{\Psi}]$, is replaced by the set of reference thermograms obtained in step 1.

STEP 3. Parametric optimization problem (2) is solved according cuboid of infrared images in each point of resolution space, resulting in getting spatial distribution of estimated values of the thermal parameters for the studied isotropic material.

STEP 4. Solution to the image segmentation problem. Thermal tomography is a reflection of numerical TPP values within the limits of the heated soil layer over depth, obtained by processing cuboid of infrared images over the entire range of observation.

Let us consider the nature of segmentation for thermal tomography over the form and TPP of monitored objects. The indication for the classification of the object are the identified TPP and their geometric parameters described by the *G* set

Aggregate of identical values of *G* set will characterize the image of the classified goal, which can be recovered by calculating the difference measure. Using a set of the estimated TPP values allows for classification of the object type as a heat conductor (metal), thermal insulator (plastic) or soil (sand, clay, soil, gravel, asphalt, concrete). Defining parameter in this case is the thermal conductivity, see Figure 1.

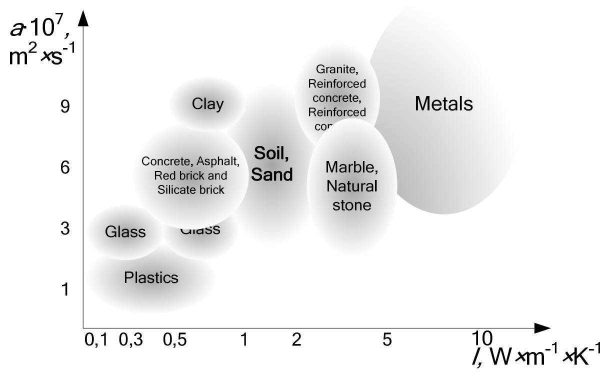


Figure 1. Classification of monitored objects by TPP

The following inequation can be used for making a decision about the discovery and recognition of the object class (at the example of the three classes: "plastic", "soil", "metal") by the thermal conductivity:

$$D_{\lambda}(m,n) = \begin{cases} 0, \ \ \Delta D_{\lambda}(m,n) \le 0,5(\lambda_{\Pi_2} - \lambda_{\Pi_1}); \\ 1, \ \ \Delta D_{\lambda}(m,n) > (0,5(\lambda_{\Pi_2} - \lambda_{\Pi_1})) \wedge (\lambda_2(n_1,n_2) > \lambda_{\Pi_2}); \\ 2, \ \ \Delta D_{\lambda}(m,n) > (0,5(\lambda_{\Pi_2} - \lambda_{\Pi_1})) \wedge (\lambda_2(n_1,n_2) < \lambda_{\Pi_1}), \end{cases} \tag{5}$$

where $m \times n$ – is infrared image raster, $D_{\lambda}(m,n) = 0$ indicates that the monitored object in point (m,n) is not detected, and, respectively, it is a material of "soil" class; an object of "metal" class is found $D_{\lambda}(m,n) = 1 -$ in flow of (m,n); $D_{\lambda}(m,n) = 2$ - an object of "plastic" class is found in the flow of (m,n).

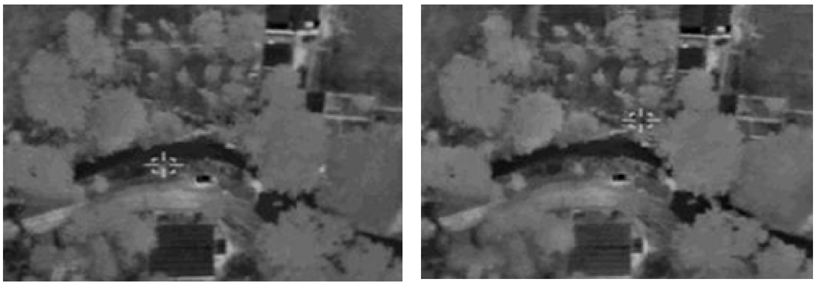
Therefore, the reduction of infrared images obtained from UAV is made by sequential solution of the following problems:

- obtaining cuboid of infrared images of the monitored object using a UAV;
- numerical solution of the nonlinear heat conductivity problem, at that thermal simulation is performed based on the results of experimental studies using reference materials;
- numerical solution of the nonlinear heat conductivity problem with the a priori data about the monitored object;

- solution of the inverse heat conductivity problem in the variation formulation;
- development of a criteria for detecting the object based on the specified thermal and physical parameters.

4. Results

We shall consider the example of solving the problem of cuboids of infrared images reduction. The images are obtained with the medium-range unmanned aerial vehicle at an altitude of 4,000 meters at night when shooting the same site area after the rain every 10 minutes during an hour and a half (Figure 2) based on a simplified mathematical model . At the infrared images, buildings, the river, tops of trees, and the car are visible.



a) time - 01:10; b) time - 02:40;

Figure 2. Infrared images obtained with the unmanned aerial vehicle

In turn, the result of a simplified solution of the problem (2) for the four reference objects (tops of trees, slate roof, water, metal) gave the possibility to obtain thermal tomogram shown in Figure 3. This Figure demonstrates locations of water accumulation, forest belt area, soil, metal objects, and residential structures.

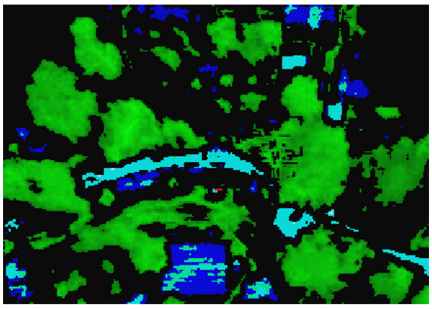
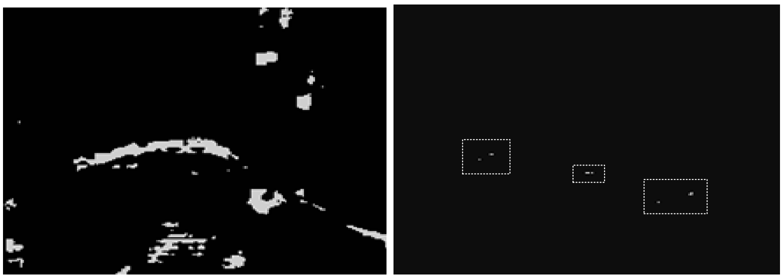


Figure 3. The results of the simplified solution of problem (2)

In addition, the use of thermal tomogram segmentation algorithms allowed highlighting objects similar in thermal parameters in the thermal tomogram (Figure 4).



a) Object "Water"; *b*) Object "Metal"

Figure 4. Segmentation result of thermal tomogram on TPP

Analysis of Figure 3*a* demonstrated that the rooftop of buildings contain water, and of Figure 3*b* revealed the location of metal pillars of suspended river flying bridge, which are actually located in these locations.

5. Conclusions

One of the most difficult problems for the numerical simulation are the inverse problem of mathematical physics equations. This class of problems is typical to have violation of the requirements of the continuous solution dependence on the input data. Introduction to the class of well-posed problems is achieved by restricting admissible solutions class by applying regularization algorithms.

Solution of nonlinear coefficient heat exchange problems with the heterogeneity of the object allows for simultaneously solution of the problem on identification of thermal parameters, and solution for image segmentation problems on their basis.

Practical measuring of thermal infrared waves show the effectiveness of thermal recording associated with the detection of metal or plastic objects. The main reason for the application of infrared systems for the solution of the detection problem of subtle objects is that soil TPP over the conductivity scale is located midway between TPP of metals and plastics, and their values differ for one - two orders from each other.

Thermographic detection methods are based on comparison of measured temperatures with the given threshold. However, low sensitivity of infrared systems and small values of temperature contrasts reduce their effectiveness as detectors.

One of the ways of increasing the probability of detection is using computational thermal physics methods for identification of TPP both for soil and for subtle objects according to dynamic infrared images. Practical experiments on TPP identification, formation of thermal tomograms and reconstruction of subtle objects listed in the paper confirm this possibility.

The main result of work is the development of information processing methods for optical electronic systems of infrared wavelengths placed on unmanned aerial vehicles based on deterministic numerical models designed to identify the parameters of monitored objects, which allows for the solution of the following problems:

1. A mathematical formulation of the problem for detecting monitoring objects in the infrared wavelengths using UAVs was defined. This formulation differs from the known by the fact that the object detection is performed by numerical solution of the direct and inverse heat conductivity problems, making it possible using the identified TPP and geometric parameters of the object to determine its size, and also classify by material (plastic, metal) and reconstruct the location.

2. Differential and simplified model of the nonlinear heat conduction problem is designed at radiation heating of flat ground surface and its convective heat exchange with the environment taking into account the low-profile of the object, which is the basis of secondary information processing from optical and electronic systems of the infrared wavelength range based on the assumptions of the theory of variation calculation.

3. Algorithm for solving the inverse heat conductivity problem for the detection of subtle objects is synthesized. Based on the developed algorithm, it became possible to obtain an image in the form of thermal tomography during the processing of information from OES using UAV.

Thus, the use of a simplified mathematical model for solving the problem of cuboids of infrared images reduction obtained with unmanned aerial vehicles, allowed revealing similar objects based on similar TPP, and thermal tomogram image segmentation allowed identification of objects invisible at the initial infrared images.

Therefore, the efficiency of monitoring the Earth's surface shall be increased by considering not separate infrared signatures of objects, but their dynamic images - cuboids of infrared images. The numerical solution of inverse thermal conductivity problem according cuboids of infrared images data allows obtaining a single image - thermal tomogram. Obtaining thermal tomograms on the results of monitoring the Earth's surface using unmanned aerial vehicles significantly enhances the possibilities of infrared images reduction (Ishchuk et al., 2014 Part 1, Part 2).

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