Method of classification of technogenic objects on the basis of construction of multilayer thermal tomograms

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Abstract The article deals with the problem of classification of man-made objects on the background of the earth's surface, under the conditions of natural heat exchange with the environment based on the construction of multilayer thermal tomograms. The results of experimental testing of the proposed method of classification are presented.

1. Introduction
In the tasks of remote monitoring of the earth's surface with the use of unmanned aerial vehicles (UAVs), increasing attention is paid to the use of multispectral optoelectronic means (MOES), which include devices of visible and infrared (IR) wavelength ranges. Their joint application allows to solve a number of important tasks, such as navigation in difficult weather conditions, detection of hidden (buried in the ground) objects, identification of their internal structure, search for victims and wounded. The solution of the above problems is based, as a rule, on the solution of problems of detection, recognition and classification of objects located on the earth's surface, or buried in the ground under conditions of natural heat exchange with the environment [1]. Among the main information features, such as shape, size, contrast, spatial location, the parameters of the underlying surface (soil), allowing to classify a technogenic object on the background of the earth's surface, a very important role, in terms of information, have thermophysical properties of technogenic objects, directly affecting the distribution of temperature fields on the surface of the remote monitoring area, the analysis of which allows you to obtain or clarify information about the object, such as linear dimensions, location in space, shape, internal structure [2].

2. Problem statement
The task of classification of technogenic objects on the background of the earth's surface is to highlight the information (unmasking) features inherent in a technogenic object.

In general, the problem of classification of technogenic objects on the background of the earth's surface can be written in the following form [3]:

\[ R_i \{ r_1, r_2, ..., r_n \} \rightarrow \Omega \{ \omega_1, \omega_2, ..., \omega_m \} , \ i \in [1..N] \]  

(1)

where \( R_i \) - classified technogenic object; \( \{ r_1, r_2, ..., r_n \} \) - a set of information features; \( \Omega \{ \omega_1, \omega_2, ..., \omega_m \} \) - set classes of materials; \( N \) - the number of technogenic objects.

Consider the area of the earth's surface with objects located on it in the form of a simplified model (figure 1) located in natural conditions of heat exchange with the environment.
Figure 1. Model of the earth’s surface with technogenic objects.

The thermal regime of the surface layer of the earth’s surface is described by the heat balance equation [4]:

\[ (1-V)Q - B_0^* = Q_M + Q_T + Q_v \]

where \( Q_M = -\lambda(\theta) \frac{\partial T(x, y, z)}{\partial z} \bigg|_{z=0} \) – the amount of heat conducted through the molecular heat transfer;

\( Q_T = C^* \rho^* k \frac{\partial T(x, y, z)}{\partial z} \bigg|_{z=0} \) – the total amount of heat released due to the turbulent heat transfer;

\( Q_v = L_p k \frac{\partial S}{\partial z} \bigg|_{z=0} \) – the total amount of heat released by evaporation (condensation) water from the surface; \( V \) – the albedo; \( Q = F' + F'' \) – the total flux of solar radiation coming to the surface; \( F' \) – the flow of direct solar radiation; \( F'' \) – the flow of diffuse solar radiation; \( B_0^* = \delta \left( \sigma T^4 - \delta_a \sigma T^4 \right) \) – effective radiation of the upper layer of the surface; \( \delta \) - absorptivity of the upper layer of the surface; \( \sigma \) – the Stefan – Boltzmann constant; \( \delta_a \) – the relative emissivity of the atmosphere; \( T_a \) – temperature of air; \( \lambda(\theta) \) - effective thermal conductivity; \( T_b = T_b(x, y, \tau) \) – function of the surface layer temperature; \( \tau \in [0, T] \) – time interval of observation; \( \Theta(x, y, z) \in \Omega \times [0, H] \) – vector of spatial coordinates; \( \Omega \) – set of permissible values; \( \Theta \) – surface of a semi-bounded medium; \( C^* \) – specific isobaric heat capacity of air; \( \rho^* \) - air density; \( k \) - turbulence coefficient; \( L_p \) - specific heat of vaporization; \( s \) - mass fraction of water vapor.

The temperature field distribution in an anisotropic inhomogeneous medium is described by the equation [5]:

\[ C_{\rho j}(\theta) \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left[ \lambda_j(\theta)_{11} \frac{\partial T}{\partial x} \right] + 2 \frac{\partial}{\partial x} \left[ \lambda_j(\theta)_{12} \frac{\partial T}{\partial y} \right] + 2 \frac{\partial}{\partial x} \left[ \lambda_j(\theta)_{13} \frac{\partial T}{\partial z} \right] + \frac{\partial}{\partial y} \left[ \lambda_j(\theta)_{21} \frac{\partial T}{\partial y} \right] + 2 \frac{\partial}{\partial y} \left[ \lambda_j(\theta)_{22} \frac{\partial T}{\partial z} \right] + \frac{\partial}{\partial z} \left[ \lambda_j(\theta)_{31} \frac{\partial T}{\partial z} \right] \]

where \( C_{\rho j} \) - the volume heat capacity of the medium; \( \theta \) - effective temperature; \( \lambda_j(\theta) \) - effective thermal conductivity tensor anisotropic medium.
The value of the effective thermal conductivity \( \lambda_j(\Theta) \) can be calculated using the empirical equation [6, 7]:

\[
\lambda_j(\Theta) = B_{0j} + B_{1j} \Theta + B_{2j} \Theta^{1/2}
\]

(4)

where \( B_{0j} = \begin{pmatrix} b_{0j}^{xx} & b_{0j}^{xy} & b_{0j}^{xz} \\ b_{0j}^{yx} & b_{0j}^{yy} & b_{0j}^{yz} \\ b_{0j}^{zx} & b_{0j}^{zy} & b_{0j}^{zz} \end{pmatrix} \), \( B_{1j} = \begin{pmatrix} b_{1j}^{xx} & b_{1j}^{xy} & b_{1j}^{xz} \\ b_{1j}^{yx} & b_{1j}^{yy} & b_{1j}^{yz} \\ b_{1j}^{zx} & b_{1j}^{zy} & b_{1j}^{zz} \end{pmatrix} \), \( B_{2j} = \begin{pmatrix} b_{2j}^{xx} & b_{2j}^{xy} & b_{2j}^{xz} \\ b_{2j}^{yx} & b_{2j}^{yy} & b_{2j}^{yz} \\ b_{2j}^{zx} & b_{2j}^{zy} & b_{2j}^{zz} \end{pmatrix} \) – matrices of empirical coefficients.

Boundary and initial conditions of layered media conjugation [5]:

\[
\lambda_j(\Theta) \frac{\partial T_j}{\partial z} \bigg|_{z=b_j} = \frac{1}{R_T} \left( T_{j+1}\big|_{z=-h_j} - T_j\big|_{z=-h_j} \right)
\]

\[
\lambda_j(\Theta) \frac{\partial T_j}{\partial z} \bigg|_{z=-h_j} = \lambda_{j+1}(\Theta) \frac{\partial T_{j+1}}{\partial z} \bigg|_{z=-h_j}
\]

\[
T_N\big|_{z=H} = \varphi_1(x, y, H)
\]

\[
T_0\big|_{z=0} = \varphi_0(x, y, 0)
\]

where \( R_T \) – the coefficient of thermal resistance; \( \varphi_1(x, y, H), \varphi_0(x, y, 0) \) – functions of the initial temperature distribution at the upper and lower boundaries of the layer.

3. Problem solution

When conducting remote monitoring with a given frequency, the values of radiation temperature and brightness of the surface of each elementary area \( g \in G \) of the earth’s surface are measured, the size of which depends on the altitude of the UAV and the resolution of the MOES and receive a set of spatio-temporal multispectral images in the visible and IR wavelength ranges – the cuboid of visible images and the cuboid of IR images.

In some cases, there are high levels of noise in the formation of images, for example, in the thermal formation of images. We will average the obtained images by taking the average value for several images and thus significantly reduce the noise level. The variance of the mean taken from \( K \) simultaneous samples is defined as [8]:

\[
\sigma_G^2 \approx \frac{1}{(K-1)} \sigma_G^2 = \frac{1}{K(K-1)} \sum_{i=1}^{K} (G_i - \overline{G})^2
\]

(6)

where \( G_i \) – the matrix of a single image from the set of simultaneous \( K \) samples; \( \overline{G} \) – the matrix of the average image. The conversion of the radiation temperature field values into the thermodynamic temperature field values on the surface is performed in accordance with the system of equations [9]:

\[
T_{id} = \left( T_r^{1-\epsilon} - T_{id}^{1-\epsilon} \right) \epsilon^{0.25}
\]

(7)

\[
T = T_{id} - T_{id} \min
\]

where \( T_r \) – radiation temperature; \( T_{id} \) – the value of the thermodynamic temperature at the \( g(x, y) \in G \); \( T_{id} \min \) – the minimum value of the thermodynamic temperature of the surface. As a result of the transformation, the equation (6), we obtain a cuboid of thermodynamic temperature images \( T(x, y, \tau) \). The amount of total solar radiation coming to the surface can be determined from the value of direct solar radiation at the upper boundary of the atmosphere [4]:

\[
Q^* = F_0 \int_{-\infty}^{t_0} \left( \sin \varphi \sin \xi + \cos \varphi \cos \xi \sin \frac{2\pi}{P} t \right) \frac{dt}{R^2}
\]

(8)
where \( F_0^* \approx 2 \ \text{cal} \cdot \text{sm}^2 / \text{min} \) – the astronomical solar constant; \( \pm t \) – the time of sunrise and sunset, counting from noon; \( R = \frac{r}{r_0} \) – the ratio of distances of arbitrary and average distances from the Earth to the Sun; \( \varphi \) – latitude of observation; \( \xi = -23.5...+23.5 \) – the angle of declination of the Sun; \( P \) – the period of rotation of the Earth; \( \frac{2\pi}{P} t \) – hour angle; \( t \) – the time counted from noon [4].

It is known that due to absorption and scattering in the atmosphere, the flow of solar radiation is attenuated by an average of 20%. The presence of clouds weakens it by an average of 20–30% [4].

Determine the average coefficient of transparency of the atmosphere in a cloudless sky [4]:

\[
p_{\lambda} = \exp(-\alpha_{\lambda})
\]

where \( \alpha_{\lambda} \approx 0.2 \) – the average coefficient of attenuation of solar radiation in the atmosphere.

The flow of total solar radiation coming to the investigated surface at cloudless sky is determined from the expression [4]:

\[
Q^0 = Q^* p_{\lambda}^m
\]

where \( m \) – the optical mass of the atmosphere; \( h \) – the height of the sun. The second equation in the system (11) is obtained empirically. For the cloudless sky, the total radiation flux can be estimated from the empirical equation [4]:

\[
Q = Q^0 (1 - (a + bn)n)
\]

where \( n \) – the amount of cloud in fractions of one; \( a, b \) – empirical coefficients (\( a \) : 0.4; \( b \) : 0.38 for \( \varphi = 50^\circ \)). The timing of total solar radiation on the surface can be described by the equation [5]:

\[
\Delta Q_j = Q \left( \cos \left( \frac{2\gamma \Delta \tau_j}{\tau} \right) - \cos \left( \frac{2\gamma \Delta \tau_{j-1}}{\tau} \right) \right)
\]

where \( \gamma \) – the maximum angle of rise of the Sun over the horizon during the day; \( Q \) – the amount of solar radiation per day; \( \tau \) - the duration of the day; \( [\Delta \tau_{j-1}, \Delta \tau_j] \) – the time interval of distribution of solar radiation \( \Delta Q_j \); \( j \in [1, \tau] \) – the number of hours from sunrise.

Construction of the spatial distribution of thermal parameters is based on the reduction of the cuboid of IR images [9]:

\[
A_{\tau}^{-1}(\mathcal{T}(x, y, \tau)) = \begin{bmatrix} f_\lambda(x, y) \\ f_{\psi}(x, y) \end{bmatrix}
\]

where \( f_\lambda(x, y) \) – thermal tomogram of thermal conductivity; \( f_{\psi}(x, y) \) – thermal tomogram of thermal diffusivity; \( A_{\tau}^{-1} \) – inverse operator using a priori information about inaccuracy in the input data, which allows to obtain a correct solution of the coefficient inverse thermal conductivity problem by minimizing the residual functional based on the numerical solution of the multiparameter optimization problem:

\[
J(f) = \sum_{G} \int_{G} \left( \xi_1 \| T_0[\psi : f] - \tilde{T} \|^2 + \xi_2 \left\| \frac{dT_0[\psi : f] - d\tilde{T}}{d\tau} \right\|^2 \right) dx dy d\tau \rightarrow \min_{f \in \mathcal{D}_f}
\]
where $\mathbf{\psi} \{ \Lambda, h, Q, Ff, T_a \}$ – the vector of the optimized parameters of the mathematical model for the earth’s surface; $\Lambda \{ \lambda_i, C_i, \rho_i \}$ – the set of thermal parameters of the mathematical model used; $\lambda_i$ - thermal conductivity of the $i$ layer; $C_i$ – specific heat of the $i$ layer; $\rho_i$ – density of the $i$ layer; $i = 1, 2$ – layer number; $h$ – modeling depth; $Q$ – the flow of total solar radiation coming to the surface under study; $Ff$ - wind speed in the surface layer; $T_a$ – temperature of air on the high 2 meters under the surface; $\xi_1, \xi_2$ – weight coefficients; $T[\psi]$ – temperature field obtained by solving the direct problem of thermal conductivity by numerical methods; $\tau \in [0, T]$ – time interval of observation; $f = \frac{f_i(x, y)}{f_a(x, y)}$ – matrix of spatial distribution of thermophysical parameters on the surface under study; $G$ – area of the surface under study; $D_f$ – set of permissible values $f$.

4. Experiment
For experimental testing, reference materials with known values of thermophysical parameters were taken:

- styrofoam $\left( \lambda = 0,026...0,09 \frac{W}{m \cdot K}; \ a = 2,03 \cdot 10^{-7}... \ 25 \cdot 10^{-7} \frac{m^2}{s} \right)$;
- wood $\left( \lambda = 0,15...0,23 \frac{W}{m \cdot K}; \ a = 6,94 \cdot 10^{-8}... \ 3,19 \cdot 10^{-7} \frac{m^2}{s} \right)$;
- steel $\left( \lambda = 40...100 \frac{W}{m \cdot K}; \ a = 10^{-5}... \ 5,5 \cdot 10^{-5} \frac{m^2}{s} \right)$;
- concrete slab $\left( \lambda = 30...50 \frac{W}{m \cdot K}; \ a = 1,05 \cdot 10^{-5}... \ 6,08 \cdot 10^{-5} \frac{m^2}{s} \right)$ located on the ground surface $\left( \lambda = 0,5...3,1 \frac{W}{m \cdot K}; \ a = 3,27 \cdot 10^{-7}... \ 17,5 \cdot 10^{-7} \frac{m^2}{s} \right)$ (figure 2).

Measurements of radiation temperatures of the surface and the materials on it were carried out by the Flir Tau 2 thermal imaging receiver from a height of 100 meters during the day at intervals of 2 hours. 12 IR images of the investigated area of the earth’s surface were obtained (figure 3).

For calculation of thermophysical parameters was used meteorological and geophysical conditions, obtained for the nearest to the venue of the experiment the meteorological station located at the airport of Voronezh Chertovitskoe (table 1) [10].

![Figure 2. Placement of reference materials on the ground surface.](image-url)
Table 1. Meteorological and geophysical conditions.

| Data, time   | Temperature of air on the high 2 meters under the surface, °C | Relative humidity, % | Wind speed at an altitude of 10-12 meters above the earth's surface, m/s | Cloudness |
|--------------|---------------------------------------------------------------|----------------------|-----------------------------------------------------------------|-----------|
| 20.06.17 08.00 | 19.0                                                                 | 68                    | 2                                                               | 0-1       |
| 20.06.17 10.00 | 22.0                                                                 | 57                    | 4                                                               | 0-1       |
| 20.06.17 12.00 | 24.0                                                                 | 47                    | 6                                                               | 6-9       |
| 20.06.17 14.00 | 26.0                                                                 | 34                    | 6                                                               | 0-1       |
| 20.06.17 16.00 | 26.0                                                                 | 39                    | 5                                                               | 0-1       |
| 20.06.17 18.00 | 25.0                                                                 | 34                    | 6                                                               | 0-1       |
| 20.06.17 20.00 | 23.0                                                                 | 41                    | 3                                                               | 0-1       |
| 20.06.17 22.00 | 16.0                                                                 | 68                    | 0                                                               | 0-1       |
| 21.06.17 00.00 | 14.0                                                                 | 77                    | 2                                                               | 0-1       |
| 21.06.17 02.00 | 15.0                                                                 | 77                    | 2                                                               | 0-1       |
| 21.06.17 04.00 | 16.0                                                                 | 72                    | 3                                                               | 0-1       |
| 21.06.17 06.00 | 18.0                                                                 | 64                    | 4                                                               | 0-1       |

Figure 3. IR images of the investigated surface area with objects located on it.

Table 4. Thermal scan the thermal conductivity a) top layer; b) bottom layer.
In the course of solving the multiparameter optimization problem (15), implemented on the basis of a genetic algorithm using a two-layer mathematical model of the surface, the optimal distribution of temperature fields on the surface and deep into the observed area with objects located on it were obtained. The solution of the coefficient inverse problem for the obtained optimal distributions of the surface temperature fields made it possible to determine the effective values of the thermophysical
parameters (thermal conductivity and thermal diffusivity) of the surface of the investigated area and to construct their spatial distribution – two-layer thermal tomograms of thermal conductivity and thermal diffusivity (figures 4, 5) and a depth chart (figure 6). Clustering pixels with similar thermophysical parameters allowed to identify areas of material classes and build their spatial distribution on the earth's surface (figure 7).

According to the obtained thermograms, the effective values of thermal conductivity and thermal diffusivity for the reference materials were:

- for styrofoam: \( \lambda = 0.07...0.13 \frac{W}{m \cdot K} \); \( \alpha = 0.01 \cdot 10^{-5} \frac{m^2}{s} \);
- for wood: \( \lambda = 0.2...0.3 \frac{W}{m \cdot K} \); \( \alpha = 0.01 \cdot 10^{-5} \frac{m^2}{s} \);
- for steel: \( \lambda = 100 \frac{W}{m \cdot K} \); \( \alpha = 5 \cdot 10^{-5} \frac{m^2}{s} \);
- for concrete slab: \( \lambda = 31...39 \frac{W}{m \cdot K} \); \( \alpha = 10^{-5}...3.5 \cdot 10^{-5} \frac{m^2}{s} \);
- for soil: \( \lambda = 1.99...3.16 \frac{W}{m \cdot K} \); \( \alpha = 0.1 \cdot 10^{-5} \frac{m^2}{s} \).

From the analysis of the values of thermal conductivity and thermal diffusivity obtained in the course of mathematical modeling, it follows that the relative inaccuracy of the reference and calculated values of thermal parameters was not more than 10% for all reference materials, which indicates the adequacy of the mathematical model used.

5. Conclusion

Thus, the problem of classification of man-made objects on the background of the earth's surface on the basis of their thermal properties is formulated. The solution of the problem is based on finding the optimal distribution of temperature fields on the surface under study using search engine optimization algorithms and numerical solution of the coefficient inverse problem for parabolic partial differential heat conduction equations. In the course of solving the problem, spatial distributions of thermal parameters (thermal conductivity, thermal diffusivity) of the earth's surface with objects located on it were obtained and their classification by classes of materials was made. The results obtained in the course of experimental testing indicate the adequacy of the mathematical model used.

6. References

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