Buried Objects Detection by Thermography

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Abstract - **Subsurface buried objects, available nonhomogenius impurity and the surrounding environment constitute a complex system with variable characteristics. The realistic nonhomogeneity induces considerable noise superposed to the thermal response of the buried object. In this paper the possibility of the active thermography application in buried objects detection is considered. The analysis is based on the mutual influence of the system scanning capacity and the quality of thermograms. The data are obtained by modeling and measuring for detection of several objects buried in the soil at different conditions.**

Keywords –**Buried objects detection, IR thermography, CFD**

I. INTRODUCTION

The known using methods for localization and identification of buried objects (by metal detectors or by ground penetrating radars) are contact or almost contact non-destructive testing methods, which usage is accompanied with high risk level, large duration and expenses [1] These motivated work on development of reliable, non-contact, safe and efficient detection method especially for antipersonnel landmines [2]. Among the methods used in researches there is the thermography [3÷5], which is potentially a rather fast and non-contact sub-surface buried objects detection method.

Generally, thermography detects differences in infrared radiation intensity emitted from the surface of an object. The differences are caused by the different heat content of the object or its various parts, additionally influenced by the surface emissivity characteristics. When a non-homogeneous structure, having different thermal characteristics, initially being in thermal equilibrium with its surrounding, is exposed to heat stimulation the temperature difference occurs in the structure as well as on their visible surfaces.

The thermal properties and burial depth of the buried object also play a role in the thermal signature at the surface. The situation becomes more complex as a result of the diurnal and annual heat flux cycles that drive the transport of heat to and from the surface. The difference in the thermal capacitance between soil and buried object affects their heating/cooling rates and therefore their associated infrared emissions. Infrared cameras are used to map heat leakage patterns from the ground which, nevertheless, makes this thermography method an anomaly identification technique. The technique essentially measures the thermal emissivity of the ground and interprets changes in emissivity as being caused by the presence of a foreign object; therefore, material characterization information is not provided.

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II. DYNAMIC THERMOGRAPHY FOR SUBSURFACE BURIED OBJECTS DETECTION

The general idea of using infrared thermography for the detection of subsurface buried objects (for example anti personnel mines) is based on the fact that the objects will have thermal properties that are somewhat different from the surrounding material. If the whole scene is submitted to energy flux that varies with time (this can be natural like a rising or setting sun or artificial like heating with microwaves) the objects will follow a temperature curve that will not coincide with that of the soil. If this difference in temperature becomes large enough an infrared image (or a sequence thereof) can be made in which the different objects can be seen. Further processing of these images could then lead to the detection and maybe the classification of the objects.

A. Analytical approach

The first step is to build a theoretical thermal model of the object buried in the soil. The problem is considered to be one-dimensional, non-stationary; and the model is constructed using the general equation of heat conduction.

The situation of the buried object will be considered as a combination of three domains: the ground above the object (domain 1), the object itself (domain 2), and the ground beneath the object (domain 3).

For each of these three domains we can write the general equation of heat conduction, which leads to:

$$\begin{aligned} \frac{\partial T_1}{\partial t} &= \alpha_{ground} \frac{\partial^2 T_1}{\partial x^2} \qquad 0 < x < x_1 \\ \frac{\partial T_2}{\partial t} &= \alpha_{\min e} \frac{\partial^2 T_2}{\partial x^2} \qquad x_1 < x < x_2 \\ \frac{\partial T_3}{\partial t} &= \alpha_{ground} \frac{\partial^2 T_3}{\partial x^2} \qquad x_2 < x < \infty \end{aligned} \tag{1}$$

Here α is the thermal diffusivity of the different regions (object and ground), t is time, T is temperature in the different regions and x is depth.

As initial conditions the three domains are considered in thermal equilibrium (all is at temperature Ti), and the thermal contact between them is considered to be perfect. Also the temperature far beneath the object remains constant.

These initial conditions can then be expressed as the following boundary conditions:

$$T_3(\infty, t) = T$$

$$\left.\frac{\partial T_3(x,t)}{\partial x}\right|_{n=\infty} = 0$$

$$T_1(x_1,t) = T_2(x_1,t)$$
$$T_2(x_2,t) = T_3(x_2,t)$$
$$k_1 \left.\frac{\partial T_1(x,t)}{\partial x}\right|_{x=x_1} = -k_2 \left.\frac{\partial T_2(x,t)}{\partial x}\right|_{x=x_1}$$
$$k_2 \left.\frac{\partial T_2(x,t)}{\partial x}\right|_{x=x_2} = -k_3 \left.\frac{\partial T_3(x,t)}{\partial x}\right|_{x=x_2} \qquad (2)$$

Here the k values represent the thermal conductivities of the domains. Application of an external thermal flux is modeled by application of a constant temperature T_f at the surface of the soil during a limited amount of time t_1:

$$T_1(0,t) = T_f \quad 0 \le t \le t_l \qquad (3)$$

After time t_1, natural convection will occur due to the temperature difference between the air and the ground. This process will be modeled as:

$$-k_1 \left.\frac{\partial T_1(x,t)}{\partial x}\right|_{x=0} = h(T_{air} - T_1(0,t)) \quad t \ge t_l \qquad (4)$$

Here h is the coefficient that expresses the heat transfert by means of convection.

The combination of Eq. (1) with boundary conditions of Eq. (2÷4) is a model which describes the object buried in the ground, from the thermal point of view. This model can then be used in a number of simulations.

B. Simulations

For the simulations the thermal conductivity k is considered constant through the whole domain, and the heat production (expressed as Q_v) is zero.

The general equation of heat conduction in its standard form is:

$$\frac{\partial T}{\partial t} = \nabla(\alpha \nabla T) + Q_v \qquad (5)$$

This will lead for a cylindrical coordinate system fixed to the center of the object to:

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (6)$$

The following considerations are expressed to facilitate the simulation programming:

1. For the air-surface interface, the heat flux is defined as: $q\ (z = 0) = h\ (Tair - T\ (z = 0))$.
2. In the radial direction a distance $r = r_{max}$ is defined where the temperature is no longer dependent on the coordinate r.
3. In the downward direction of z a distance $z = z_{max}$ is defined where the temperature remains constant.
4. Since the model has a cylindrical symmetry, the temperature function on a diameter of the cylinder is an even function and the temperature extreme will be on the axis $r = 0$.

The problem was discretized, using the finite volume method, a method where the domain is seen as a number of elementary volumes, each of which is in contact with its neighbors, exchanging heat. The heat conservation equation is then expressed on each of these surfaces.

The simulated object (for example a mine) has a cylindrical shape (10 cm diameter, 2 cm height), z_{max} is set to 50 cm, and r_{max} to 35 cm. For the size of the elementary volumes 5 mm is chosen according to the z axis, and 2 mm in radial direction. The simulations were done considering two different types of ground: soil and sand.

Two types of thermal fluxes are considered: natural convection, which will simulate the natural air temperature changes due to sunrise and sunset, and external stimuli, in which the surface will be heated in an artificial manner.

For the natural convection the initial uniform temperature is set at 15 ^oC. The air temperature is set at 0 ^oC during 12 hours and for the next 12 hours at 15 ^oC for the sand and at 25 ^oC for the soil.

Fig. 1 shows the evolution in temperature difference on the surface between the ground above the mine and that far away from the object, for a 24-hour cycle, and for two different depths. Fig. 1a shows this for the soil, and fig. 1b for the sand.

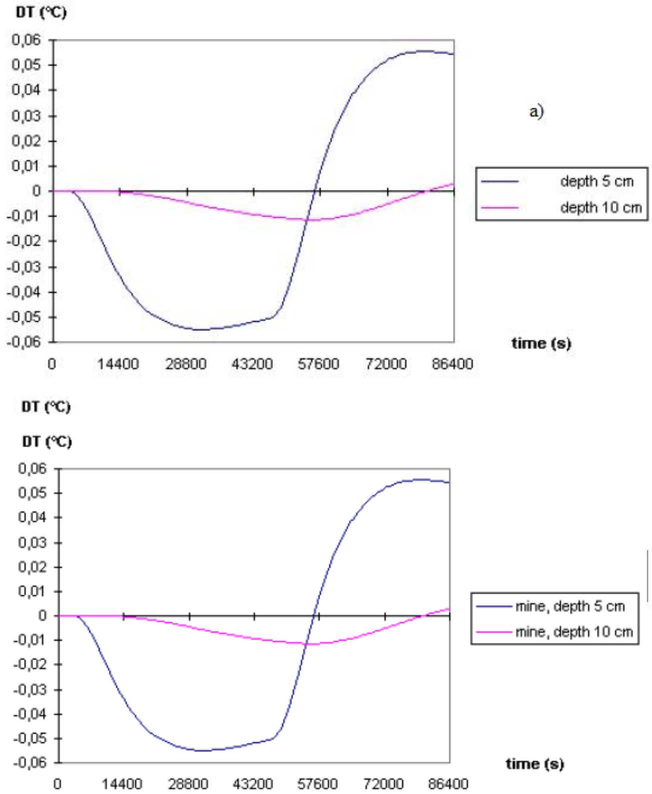


Fig. 1. The evolution of the temperature difference on the surface between the ground above the object and that far from the object, due to natural convection. (a) for soil, and (b) for sand.

The application of an external stimulus is applied to the surface of the ground containing the object. The intensity of this stimulus is fixed at 100 ^oC during two hours.

Fig. 2 represent the temperature difference for three depths 5, 10, and 15 cm, for the both types of soils.

Out of these graphs one can estimate the Minimum Resolvable Temperature Difference (MRTD) of an IR camera needed to get a detection of a buried object (or mine detection).

C. Comparison with realistic experiments

In order to verify the proposed model and to validate the simulations described above, a number of outdoor as well as laboratory experiments were performed.

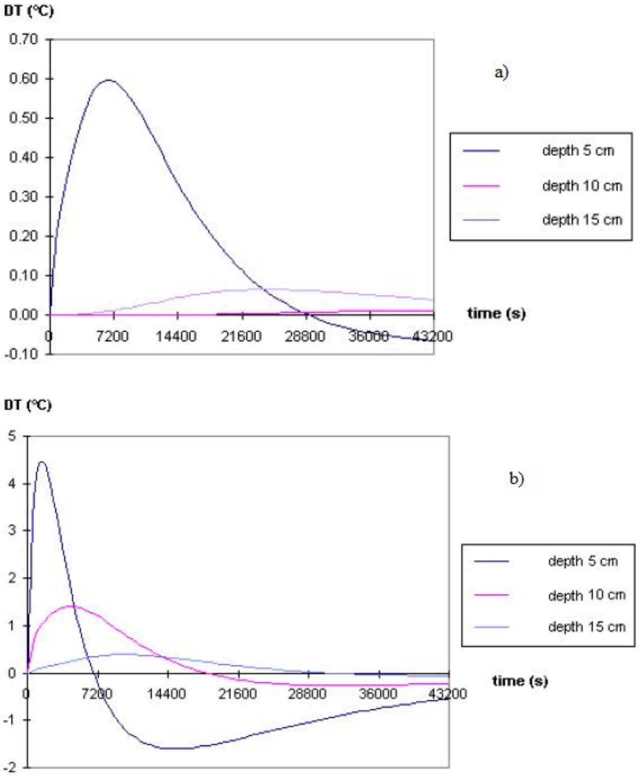


Fig. 2. The evolution of the temperature difference on the surface between the ground above the object and that far from the object, due to an external stimulus. (a) for soil, and (b) for sand.

The 24 hour cycle of objects similar to mine placed just below the surface at 5 cm depth in sand, soil and gravel was monitored. The images were taken every 30 minutes with an IR camera in the spectral band of 7,5 to 13 microns.

III. Methods and Materials

We report on thermal infrared recordings measured under different conditions. Three soil test boxes of 100×30×20 cm dimensions were constructed**.** The boxes have been filled with three different types of soil: a well-sorted sand, a typical loam soil with some (<5%) larger gravel, and a clay soil (~70% clay-size fraction).

The two buried objects used in this work were cylindrical shape objects with radius of 0,5cm and height of 3cm – one of steel and the other of plastic. The samples were buried at 0.01, 0.02, 0.03, 0.05 and 0,07 meters depth in the boxes. We used the ThermaCAM SC640 infrared camera manufactured by FLIR Systems Inc., Sweden, for measurement of the apparent temperature of the soil surface above and away from the buried objects. This IR (infrared) camera has a spectral range from 7,5 to 13 μm with thermal sensitivity of 0,08°C at +30°C. It uses a FPA noncooled bolometric array with 640x480 pixels. The sequences of thermal IR images were analyzed using the ThermaCAM Researcher Pro2.9 software provided by FLIR.

Experiments are carried out on the next sequence of work. The surface is heated (by infrared heater) and then cooled for every different type of soil and depth of buried object. The transient heating/cooling processes are saved in sequences by the infrared camera. All tests are done for metal object as well as plastic object. On the next Fig.3÷7 are shown some selected thermograms and a fragment of dynamic of cooling and heating, respectively for different test box with buried objects.

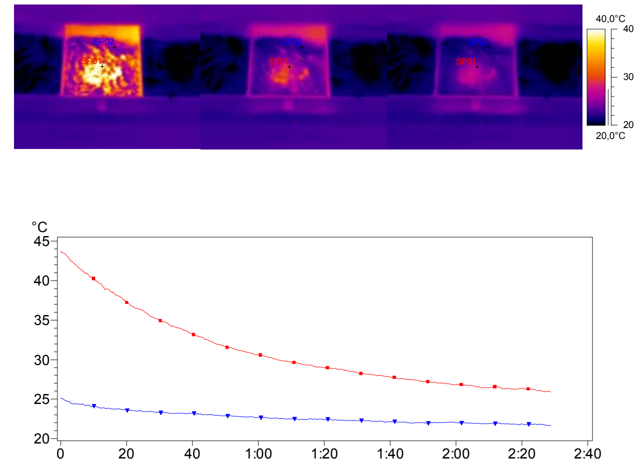


Fig. 3. Thermograms and dynamics of cooling for the steel object buried at 0,01 m depth in a sand test box

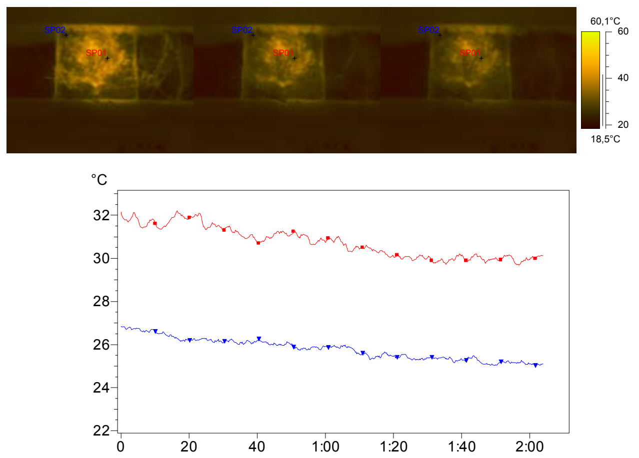


Fig. 4. Thermograms and dynamics of cooling for the steel object buried at 0,07 m depth in a clay soil test box

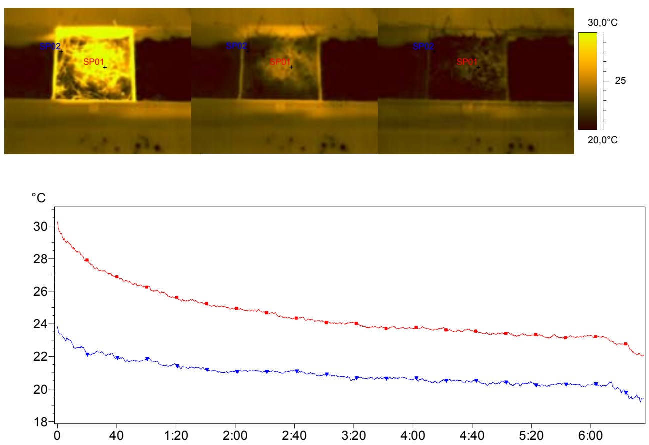


Fig. 5. Thermograms and dynamics of cooling for the steel object buried at 0,02 m depth in a clay soil test box

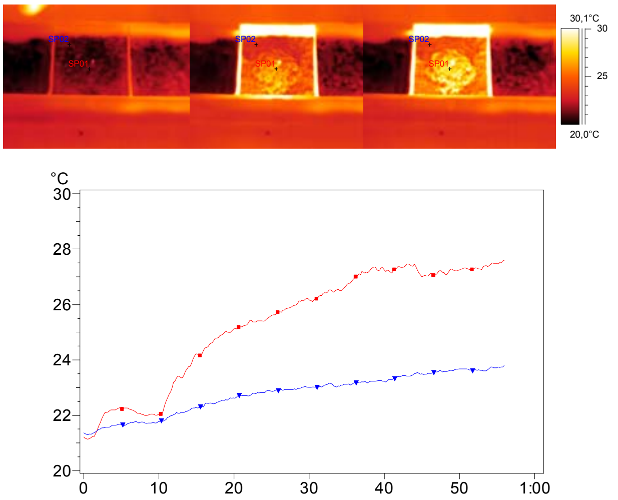
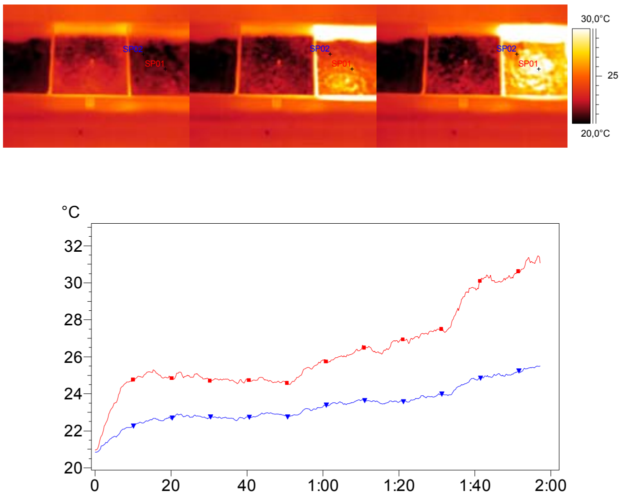


Fig. 6. Thermograms and dynamics of heating for the steel object buried at 0,02 m depth in a typical loam soil test box



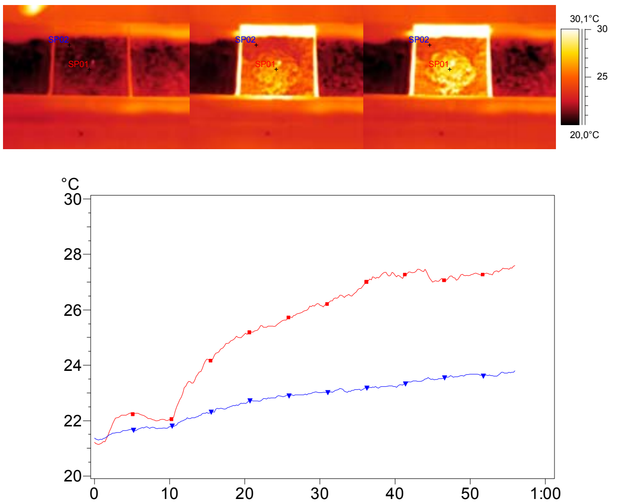


Fig. 7. Thermograms and dynamics of heating for the plastic object buried at 0,03 m depth in a typical loam soil test box

The noise reduction is realized by ICA thermogram processing algorithm. Humidity, temperature and structure of the soil are main factors highly affecting the condition of thermography tests. The results for buried plastic object are comparable with those for metallic object.

IV. Conclusion

The thermography technology has the advantages of being passive, can be performed remotely, by aerial search, and can cover a large area in a short time. Infrared thermography is best suited for identifying minefields (global area search), rather than searching for individual mines (local area search). It cannot, however, work when the soil and buried object are in thermal equilibrium, and therefore is generally limited for use either at sunset or sunrise where a temperature gradient can be established at the ground surface.

Burial depth of buried object has an effect on the temperature at the surface, and thus its thermal signature. There was a remarkable phase shift which increased with burial depth. A change in burial depth from 1cm to 10cmcaused the maximum positive peak to shift from 46.5^{0}C to 38.0^{0}C .

The plot showed that the temperature difference decreased with depth. A change in burial depth lead to a phase shift of the temperature curves. The amplitude variation decreased rapidly for deeper burial depth and any significant amplitude variation was absent for deeper depth.

The thermal signatures of the buried objects reached their peaks at times which depend on the depth of burial. It was also observed that the temperature of the emitted heat by the buried object decreased with burial depth.

For depth of 1cm the peak temperature occurred between 44^{0}C and 47^{0}C while for 40cm it occurred at 30^{0}C.

Realistic non-homogeneity induces considerable noise superposed to the thermal response of the buried object. One source of noise is surface non-homogeneity, interpretable as a quasi-random signal, which screens the thermal response of the buried object. This interpretation allows for noise reduction using advanced thermogram processing algorithms.

Acknowledgments

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