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Advanced analysis of thermograms of buried objects in non-homogeneous environment

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Abstract

The application of thermography to detect buried objects (e.g. antipersonnel mines in the humanitarian demining) has been limited to mine-contaminated regions with homogeneous and vegetationless soils. 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, such as *Independent component analysis*. We apply it to thermograms obtained using controllable experimental conditions and a realistic three-dimensional, non-stationary heat transfer program. Numerical estimates of the degree of soil non-homogeneity, which can be reduced in thermograms, are obtained for a particular, representative class of buried objects and soil surface non-homogeneity. In particular, the dependence of the results on concentration of surface point-like non-homogeneities is determined.

1. Introduction

Humanitarian demining is a set of processes, which transforms a mine affected region into a region which is safe for people. There is a significant discrepancy between the existing humanitarian demining clearance rate and the rate needed if the mandatory goal of *mine free world* is to be fulfilled till 2010 [1]. It has been shown that mine detection is responsible for most of the duration and risk related to humanitarian demining [2]. The discrepancy is a basic motivation for numerous R&D projects oriented toward improving mine detection methods and techniques [3]. One of the methods in consideration is infrared thermography (IRT) [4], which is potentially a rather fast, and non-contact mine detection method. These preliminary characteristics have been thoroughly investigated within recent years. However, overall, IRT has only occasionally been exploited in military demining, and not at all in the humanitarian demining. IRT development is still within the laboratory set-up because IRT does not achieve a reliable detection of most buried mines and a discrimination of other types of buried objects.

Therefore, if some progress in IRT application for mine detection in humanitarian demining is to be expected, then this characteristic should be used as a starting point for a rather different IRT testing. This recognition motivated us to formulate a qualitatively different IRT based buried object detection technique. The phases of the approach are (i) to analyse and parametrise the factors which cause the IRT application results, (ii) to extract a small set of highly influential factors, and (iii) to formulate the IRT technique which overcomes the negative influence of the extracted factors.

The first phase was conducted in recent years through a combined experimental work and numerical simulations [4, 5]. In the second phase, it became clear that in order to enhance the applicability of IRT in mine detection, a completely different approach is needed that includes methodology, realisation, and governing procedures. The buried objects are searched on the base of thermograms (which are 2D representations of transient thermal response of soil surface) which contain a significant level of thermal noise. Therefore one needs to find generally factors within the processes and structures

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that cause thermal noise on thermograms. The soil non-homogeneity and vegetation layer are extracted as the two mine-environment sources of thermal noise. The buried object, i.e. a mine or some other object, contributes itself to the suppression of the probability of detection, through the variability in orientation with respect to the surface normal of the local soil.

During the preliminary work, i.e. along with the first two phases, a third phase took place. It resulted in the formulation of a new approach of IRT to detect buried mines and other buried objects where the emphasis is put on thermogram evaluation. The first part of the thermogram evaluation is the removal of noise. As the level of noise is high and the signal from the buried object usually too low to be directly extracted (visually detected, or using other likelihood-setting approaches), this noise removal cannot be performed as image processing based on local transformations. Though it represents the significant part of thermogram information, the noise is a redundant part preventing the extraction of a rather small thermogram information content related to the buried objects. Therefore, the characteristics of realistic mine environments induced a significant requirement to IRT techniques applicable in humanitarian demining, in that they should start with an advanced thermogram noise removal. The approach incorporating these facts is **de**tection of **m**ines by **e**xtracting **t**hermogram **r**edundancies in an **a**dvanced way (DEMETRA). It is to be emphasised that such an approach is not needed in the “traditional” applications of IRT in Non-Destructive Testing.

The DEMETRA approach is based on the assumption that non-homogeneities of the mine environment and the mines themselves (or other buried objects) have significantly different thermal responses, hence different statistics of corresponding representations on thermograms. Within an appropriate statistical context they can be considered as independent components. By concentrating on thermogram analysis, implicitly the algorithms for signal processing are introduced. Furthermore, the fact that in a thermogram one observes a convolution of different underlying statistics serves as a rather stringent restriction to admissible signal processing algorithms.

In this paper the DEMETRA approach and preliminary results are presented. The range of validity of the results obtained is in laboratory conditions for a rather restricted type of surface non-homogeneities. Lines of future development are discussed. The main point of the DEMETRA approach is to formulate an IRT technique in which the influence of the overcritical level of thermogram noise is overcome. For the purpose of preliminary investigation of the proposed approach, the *Independent Component Analysis* (ICA) algorithm [6] was exploited in thermogram analysis.

In the next section the basics of ICA are presented, and their relevance to IRT discussed. In the third section we discuss the experimental set-up for evaluation of preliminary application of ICA to IRT based detection of buried objects. The numerical simulation applied to the proposed technique is described in the fourth section and the obtained results in the fifth section. Discussion and future development are presented in the sixth and seventh section, respectively.

2. Basics of *Independent Component Analysis*

Let us assume that N different linear mixtures of N statistically independent signals are recorded. The fact that in the origin of the records there are N independent signals can still be used as a starting point of extraction of each of the components. The specific characteristic is that each of the component signals has a relatively small information entropy, as it is subjected to some underlying set of rules. In that way, extremisation of the information entropy for the collection of records in N component space brings about the initial, non-mixed independent components up to the correct relative scale and sign of the components. The thorough introduction to ICA is freely available [6]. While originally ICA was developed for time-dependent signals, its use was subsequently broadened to photographs and other multi-dimensional structure analysis.

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Operationally, assumptions for the applicability of ICA are: (i) independence of components to be revealed; (i) unimportance of relative scale and phase and (iii) a specific requirement for the number of Gaussian distributions of signals, what is in practice regularly encountered as a restriction to noise character.

An example of ICA application is useful. In it, the example two linear combinations of 1D functions, sinus and a random noise, were obtained numerically. The ICA was applied onto resulting combinations. The mixed combinations with a rather low signal to noise ratio, and the independent components as revealed by ICA are shown in Figs. 1a and 1b, respectively. In this example, and in all subsequent applications of ICA, the software FastICA Version 2.1. is exploited.

3. Experimental set-up

In the experiment (Fig. 2a) a specimen is buried in a homogeneous soil with a relatively smooth and flat surface. The soil surface is covered with smaller objects of known shape, dimensions and material. The coverage factor *p* is introduced as a ratio of the area of soil surface covered uniformly with objects and the total area of soil surface heated. In that way the origin of thermal noise of controllable intensity is introduced and one can investigate its influence on the quality of thermal signatures of buried objects.

The experimental set-up for active IRT configuration was used [4]. It includes a box filled with sand where three specimens (steel discs of equal dimensions) are buried during one experiment cycle. This choice of specimens is influenced by their exploitation in other related experiments which contributes to the easier comparison of the obtained results, i.e. it enhances the continuation of experiments. The sand surface is covered with aluminium foils, Fig. 2b, with a coverage factor *p* ranging up to 0.3. In order to simplify the comparison with numerical simulation, the foils are squares of 5 mm side length. Using a heater, a transient non-uniform surface temperature distribution is obtained, which is recorded using a liquid nitrogen cooled thermocamera AGA 680. Thermograms are recorded in colour and intensity mode and subsequently transformed into the topography mode for the purpose of the analysis. Thereafter copper-constantan thermocouples are put into characteristic locations in the sand in order to assure the realistic temperatures achieved on the heated surface and in other regions of interest, and for comparison with simulations and experiments to be done. The reading of the thermocouples is done by a personal computer. Starting from room temperature, the soil above the buried cylinders is heated 5 min with 6 $kW \cdot m^{-2}$ heat intensity. The thermograms with large enough thermal contrast are recorded during the first 6 minutes of cooling.

4. Numerical simulation

The numerical analysis of heat transfer is based on the control volumes method. The control volume’s net formed is of variable density in order to compensate for the differently large thermal gradients. The larger number of control volumes in these regions allows for a better insight into the temperature field. Buried objects are introduced through the local change of thermal properties. Surface noise, i.e. the representation of vegetation layer (see section 3) is introduced through local changes in surface emissivity.

Initially, the temperature distribution is uniform. Boundary conditions are set for distant planes where the temperature is considered constant and equal to the initial temperature. Positions of these planes are determined so that there are no spurious heat sources registered near the buried objects during the simulated duration of the experiment.

5. Results

Thermograms of triples of buried objects are shown in colour mode, intensity mode, and topography representation (Fig. 3). From left to right in the thermograms, the depths of objects are 10 mm, 13.5 mm and 7 mm.

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The simulation revealed the surface temperature distribution in more detail (Fig. 4) and allowed to determine the optimal frequency for thermogram recording.

The ICA is applied to parts of thermograms belonging to a particular object. In Fig. 5a the details of thermograms shown in Fig. 3b are presented for $p = 0.1$ and $p = 0.3$. In Fig. 5b the results of FastICA 2.1 software for corresponding thermograms are shown. In transforming the thermogram as a 2D scalar array into sequences of N components, only the simple scanning was used. After several attempts the number of 4 independent components gave the best results.

6. Discussion

In the cases shown in Fig. 3 and 4 the coverage appears colder on all thermograms because of the relatively small thermal emissivity of metal. The thermal response of buried objects influenced the temperature distribution of buried objects, hence in the experiment the thermal noise and buried object response were not independent. This fact suppressed somewhat the results obtained by FastICA 2.1 software. The graphs in Fig. 5b show that the result of ICA (beside a by-part isometric transformation) appears as an enhancement of noise in thermogram regions which do not belong to the signature of the buried object. This differs from the situation in Fig. 5a where noise is comparable to the object signature. Such a distribution of noise is considered as a consequence of separation of independent components.

Having in mind the basics of ICA and the experiment undertaken, it is seen that not all requirements of ICA are fulfilled: (i) the coverage and the thermal response of the buried object are not independent; (ii) it is not clear to which extent sequences obtained after scanning of the initial thermogram represent records obtained by different recording devices. The fulfilment of these requirements is connected with the significant change in the character of experiments. From the present point of view, the requirement (i) is overcome by time-profiled heating. A particular example is a combination of a constant heat flux onto which at the end of heating the stronger heat pulse is superimposed. This way, due to the relatively small heat conduction rate, the heat pulse would set the representation of the surface on the thermogram, while the buried object would be represented by the long-term constant heat flux. Hence, these two signatures would be statistically relatively independent. Regarding requirement (ii), possibly a combination of two thermograms (either obtained by two thermocameras in the same moment, or by one thermocamera in different yet close moments) is to be used as an input to ICA. Along with these possibilities, a number of questions arise regarding both the substantial character of the experiment undertaken and the technical aspects. Partially this is a consequence of the missing experience, as to the authors' knowledge this is the first application of ICA to thermography.

7. Summary and lines of future development

The presently observed inapplicability of IRT in the detection of objects within an inhomogeneous medium (i.e. buried mines in the humanitarian demining) is used as a starting point for the design of qualitatively different techniques. In this paper, a combination of standard active thermography and advanced software processing is described. The results obtained imply the necessity of mutual change of both the active thermography configuration and thermogram processing software. The limits of the configuration used in the experiment and proposed configurations will be determined in future experiments.

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http://dx.doi.org/10.21611/qirt.2002.006

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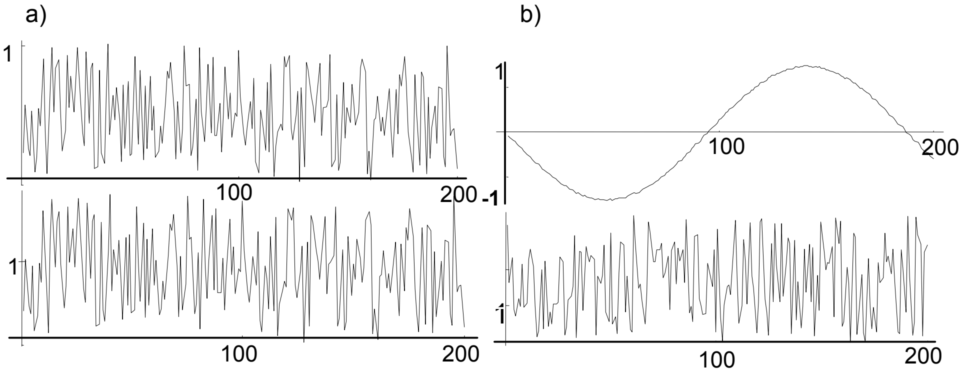

Fig. 1. *a) Two linear mixtures of sinus and a random noise, b) independent components of case a) as revealed by software FastICA 2.1.*

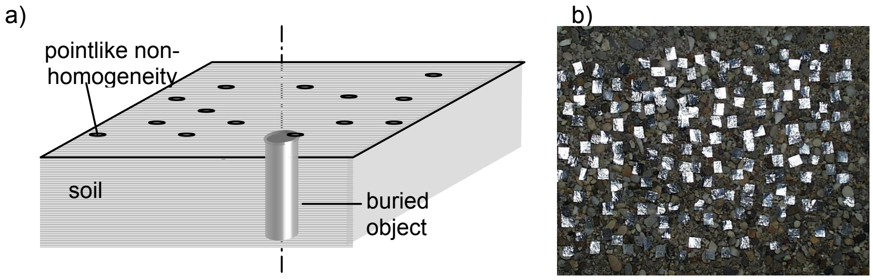

Fig. 2. *a) Sketch of the relevant structures in the model, b) surface above specimens for* p *= 0.3*

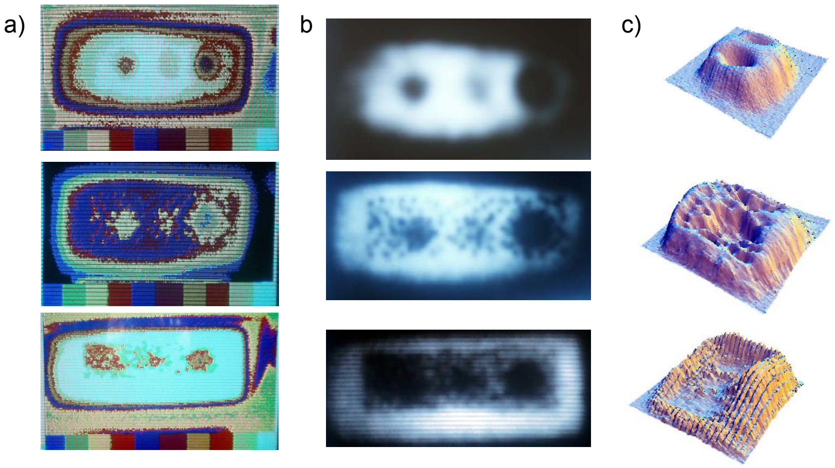

Fig. 3. *Thermograms obtained, a) in colour mode, b) in intensity mode, c) in topography mode. Coverage factor is from the first r ow down equal to 0, 0.1 and 0.3.*

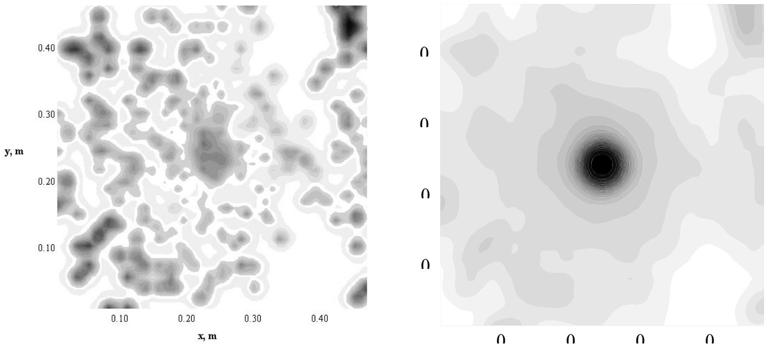

Fig. 4. *Simulated surface distribution of temperature for 300 s of heating with* p *= 0.1. A cylinder is buried on the axis through the middle of the graph. a) 0 s of cooling, b) 300 s of cooling.*

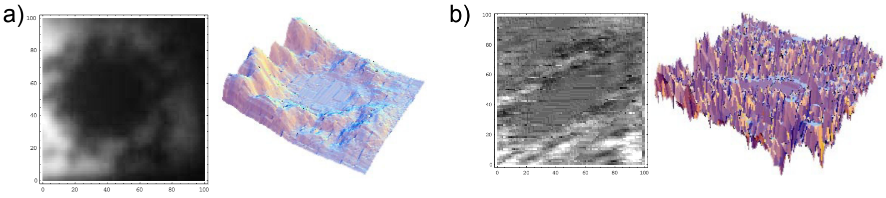

Fig. 5. *Thermograms of the object buried at 7 mm depth, for* p *= 0.1 a) before and b) after ICA.*