A new concept for thermal mine detection by local heating

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Abstract

A new concept for antipersonnel mine (APM) detection is proposed. The detection system is based on a focused heat source and a contactless thermometer mounted on a head scanning the soil. Presence of heat capacity and diffusivity anomalies (mine candidates) is assessed from anomalies in the temperature measured after the local heating.

Main advantages of the proposed system are simplicity of the device (that is cheap to realize, and easy to use and repair), power efficiency, speed.

The feasibility study presented is based on 3-D simulations.

1. Introduction

Antipersonnel mine (APM) and unexploded ordnance (UXO) detection by natural or artificial heating has been the object of increasing interest in recent years [1-8]. In fact, the metal detector traditionally employed for this task is increasingly less useful because metal content of mines has been drastically reduced.

The basic principle underlying thermal detection of mines is a difference in heat conduction and capacity of explosives, that causes a temperature difference to appear on the surface of soil over a buried mine with respect to other areas when the surface is naturally or artificially heated and/or cooled (dynamic thermography).

Thermal mine detection has the advantage of being sensitive to the bulk material of the mine regardless of metal content, and of employing quite simple and safe stimulation, either by sunlight, or by lamps, microwave heaters, hot water, etc. Other kinds of emerging detection techniques involve e.g use of ground-penetrating radars, that are not very efficient for mines lying near the surface, and in damp soil, or high-energy neutrons, requiring bulky and complicated apparatus.

The main drawback of existing thermal methods is time required (the proposed heating/cooling processes evolve on a time scale of hours). Moreover, temperature contrast is rather low, so that images obtained are noisy and require complicated post-processing. The cameras themselves are rather expensive and not easily serviceable, and the interface to the operator is not very simple and intuitive, (as e.g. for the metal detector), while danger and stressing conditions of the work require the simplest possible detection warning scheme.

In this paper, I propose a new concept for thermal APM detection, based on local heating to deliver more energy in less time, and pointwise temperature scanning by a simple and inexpensive infrared thermometer. The system works by scanning the surface along a line, delivering a strong energy pulse at each point, and reliably measuring large temperature differences after a heating/cooling cycle.

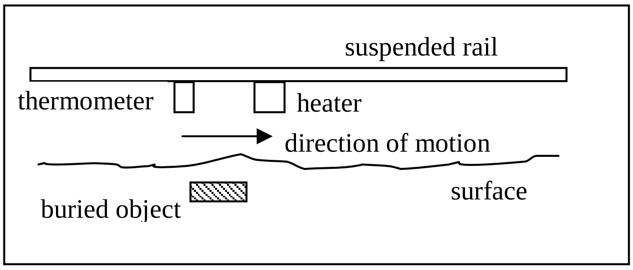

Fig. 1: structure of the proposed device.

2. Proposed detector

The basic structure of the mine detection device proposed is composed of a focused heater and a contactless thermometer, mounted on a suspended holder that progressively scans the surface under test. The heater delivers power to a small area (or volume near the surface) with dimensions comparable to those of a mine, and the thermometer trails it at a fixed distance, measuring the temperature of the surface (Fig. 1). The soil and any object, within the limited volume affected by the heating, receive a strong heat stimulation (e.g. 100KW/m^2 on the surface), that takes in time the shape of a narrow rectangular pulse (e.g. lasting 10 seconds). Such stimulation produces a rapid increase of temperature, followed by exponential decay by heat diffusion and convection/radiation from the surface. When an object having different thermal properties from the background is present, the rates of increase and decrease of the temperature are changed, so that an anomaly in the surface temperature will be generated. The thermometer trailing the heater measures surface temperature during cooling, with a fixed delay after the heating pulse, and the signal obtained from it while the device scans a narrow stripe on the surface under test can be easily processed to detect such anomalies. In fact, it is expected that on the surface over a foreign body the temperature measured will be different from elsewhere. As an example, Fig. 2 shows temperature measured in the area around the mine as obtained from the simulation described below.

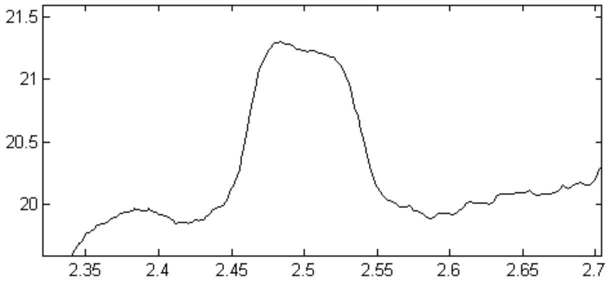

Fig. 2: Simulated surface temperature (°C) versus position (m). The mine is buried between abscissae 2.46 and 2.54.

For the heating, two most realistic possibilities can be considered among others: light and microwaves.

Using light, an infrared source (e.g. halogen lamp, heating rod) is mounted on the device as heater, and its light focused by a lens. Eventually, it might be carried by an optical fiber, which however is rather selective for infrared radiation. Light-based heating is simple and inexpensive. Its drawback in involved in the fact that energy is absorbed on the surface only, so that it takes some time to reach buried objects, and that surface anomalies (cover, roughness, inclination) may induce undesired artifacts.

Use of microwaves is also an interesting option, having the main advantage that energy can be delivered directly within the volume being scanned, and absorbed with better efficiency. However, humidity can severely limit reachable depth. A possible, more serious, problem with localized microwave heating is generation of sparks or excessive localized heat, in particular in small metallic parts within the mine (detonator), that could blow the mine up. For this reason, this feasibility study is focused on light-based heating.

For the thermometer, industrially available non-contacting infrared thermometers (pyrometers) without cooling are adequate to the task. Such devices can reach sensitivity of 0.1°K, and the absolute precision is by no means an issue, because detection is based on temperature change rather than on its actual value. Also stability of measurement need not be very tight, because only short-term differences are significant.

It is to be noted, that the main characteristic of the proposed system is local measurement of temperature change, while in principle the heater need not be strongly focused. This means that also non-localized heating (e.g by non-focused lamps or microwaves, hot water, etc.) might serve the same purpose. However, there are two good reasons for using local heating: the first is that having a rather limited amount of power available (as is reasonable for portable devices and power generators), by concentrating it in a small volume we obtain stronger heat stimulation (i.e. wider temperature change). The second is that progressive scan of the surface involves returning near areas already scanned, so that it is better if heating of previously scanned areas does not induce artifacts in the new area under test. Moreover, mine detection is best performed (as described below) during cooling, and this process is faster if the surrounding soil stays cooler than the area being scanned.

3. Simulations

3.1. Simulation setup and case study

In order to evaluate feasibility of the proposed system, its functioning was simulated in three dimensions by a finite-difference in time domain (FDTD) method using a fourth-order Adams-Bashfort integration algorithm.

A representative case study is reported in the following.

This simulation refers to a mine modeled as a cylinder of uniform material, having diameter of 8cm and height of 2, buried 1cm under the surface in dry sand. To make the simulation more realistic, the physical parameters of the sand are modeled as stochastic values with Gaussian distribution, 10% standard deviation, having exponentially decreasing correlation within a distance of about 2cm. Thermal parameters used for soil (mean values) and mine are listed in Table 1.

	density (Kg/m^3)	thermal conductivity (W/m°K)	specific heat (J/Kg°K)	diffusivity (m^2/s)
sand	1650	0.75	710	6.4 10^{-7}
mine	1350	0.4	1120	2.6 10^{-7}

Table 1: thermal parameters used

The grid for simulation covers a surface of 5×3m^2 and depth of 2.5m. The grid has approximately 1,500,000 points, with an internal volume of 30×12×6cm^3 with uniformly-spaced grid points at 0.25cm from each other, and quadratically spaced points outside this volume up to the boundaries of the simulated space. The temperature of the bottom surface is fixed at 5°C, on the side surfaces zero-gradient boundary conditions are imposed, and on the top surface convective (convection coefficient 2.1W/m^2) and radiating boundary conditions are imposed assuming air and sky temperature of 15°C.

Initial temperature of the whole volume, including the mine, is imposed with a linear gradient from 10°C at the surface to 5°C on the bottom boundary, according to depth.

Total heater power is 300W and the area heated is a circle of 6cm diameter, so that radiated power is 106KW/m^2, at least two orders of magnitude greater than sunlight. Absorption rate of 20% at the surface is assumed. The heater and thermometer move at a speed of 0.5cm/s, starting with the heater 30cm before the center of the mine, and ending 43cm after it. The scanning line passes through the center of the area over the mine, and a point lying on the line receives radiation from the heater for about 12 seconds.

Sun radiation and contribution of wind to convection normally cause an increase of temperature differences simulated, in any case of very small value due to the short time frame of the phenomena considered. Therefore in the simulation presented we neglected such contributions, so that all differences obtained are due to the artificial heating process.

In order to avoid numerical artifacts, heater power increases linearly from zero to full power in the first and last 13cm of operation. Simulation starts when the heater is switched on, and lasts for some time after it is switched off, for a total 260s.

Fig. 2 shows temperature measured 70 cm behind the heater vs. the position where the measurement is taken. At each point in space, the measurement takes place 140s after the heater was centered over it. The mine is situated between 2.46 and 2.54m. It is apparent that the anomaly caused by the mine is very evident, and can be detected even without post-processing.

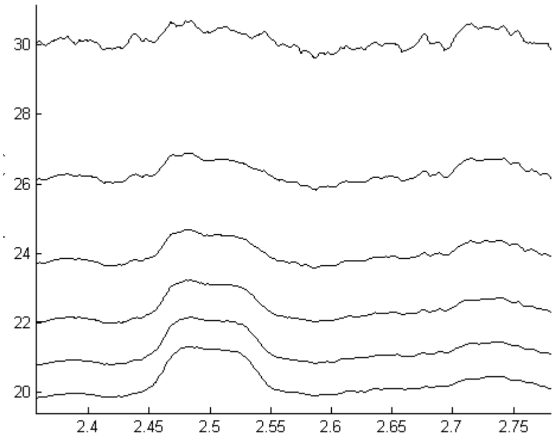

Fig 3: Simulated surface temperature (°C) vs. position (m) at several distances form the heater

Fig. 3 shows temperatures measured at distances varying from 20cm (top line) to 70cm (bottom) behind the heater, i.e. between 40s and 140s after heating each point. It is apparent that discrimination increases with time. This is due in part to reduction, due to heat diffusion, of the noisy component caused by non-uniformity of soil, but mostly to the physical mechanism of the phenomenon.

In fact, at the beginning heating only affects the very surface of soil, so that presence of the mine makes nearly no difference. As heat diffuses downwards, the mine absorbs it and makes further diffusion slower, so that the surface above it becomes warmer that the rest. As time passes, while the whole volume cools down, the mine keeps warmer due to its larger heat capacity, and for this reason temperature difference at the surface increases further. Such mechanism is illustrated in Fig. 4, that shows isothermal lines in a section of the soil through the center of the mine taken just after the heater has left the mine area, and at two subsequent times.

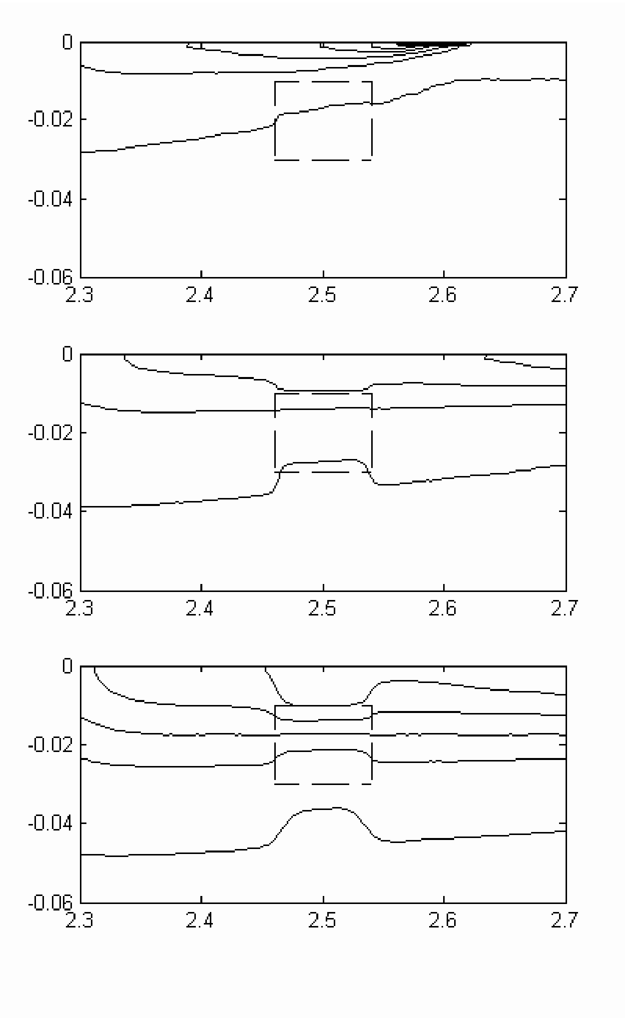

Fig. 4: Isothermal lines in a vertical section through the mine oriented along the scanning line. Mine position is indicated by dashed area, Ordinate is depth, abscissa horizontal position (m). Result taken 6s after the heater has left the mine area (top), 84s after (middle), 188s after (bottom). The lowest line is at 10°C, others are at increasing temperature towards the surface, spaced by 10°C

The thermal situation at the surface at time 260s, i.e. 200s after the heater has passed over the center of the mine is shown in the top panel of Fig. 5, and in the same conditions, a plot of the temperature along the vertical center line of that figure is given in the bottom panel of the same figure. The peak on the left corresponds to the mine, the one on the right to the position where the heater was switched off. Temperature would appear increasing towards the right up to the heater position, if the latter were still on.

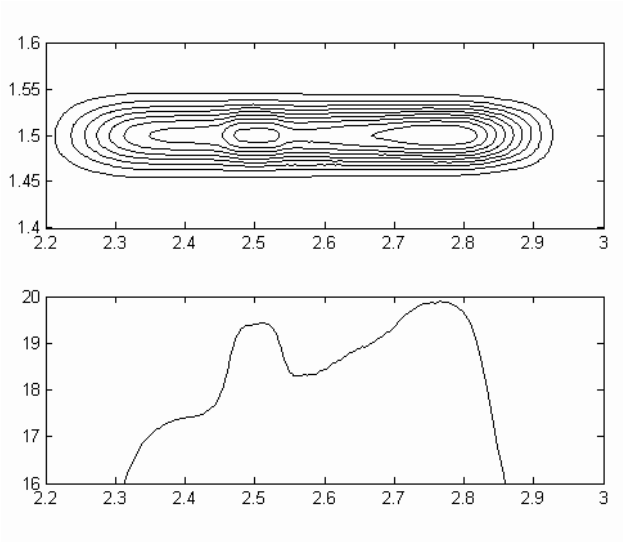

Fig. 5: Surface situation 200s after heating. Top: isothermal lines, spaced by 1°C, the innermost being at 19°C. Bottom: temperature (°C) vs. position (m) along the scanning line.

Parameters of the heater (total power, diameter, speed) where chosen empirically based on a wide set of simulations in the aim of obtaining large temperature difference and reasonable scanning speed, while avoiding excessive maximum temperature on the surface so as to keep within a reasonably safe range in case the mine is very close to the surface. Fig. 6 shows temperature vs. time at several depths at the center of the area above the mine, and within it.

When a mine is buried deeper, of course using the same parameters it is detected with increasing difficulty. While this setup works at larger depth, in order to reach deeper mines it may be necessary to increase the amount of energy delivered, in particular by reducing scanning speed. This causes an increase of maximum surface temperature, and ensuing risk of blowing up mines lying near the surface. A possible solution to the problem may be found in scanning the surface twice, first at lower energy, and then at higher energy, but avoiding areas where the first scan has detected possible buried mines.

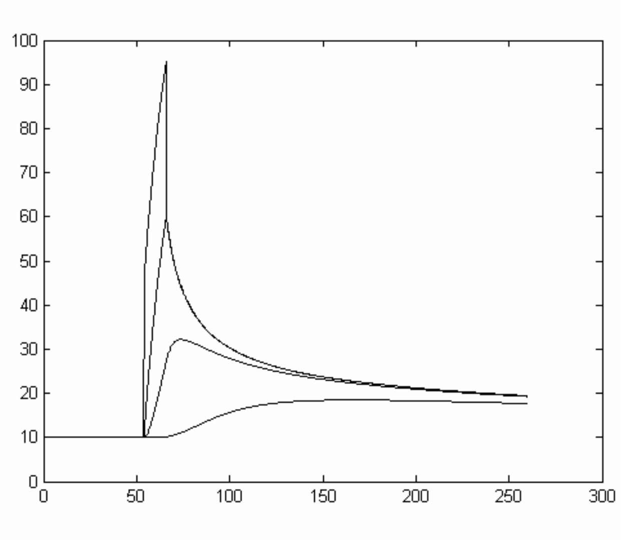

Fig. 6: Temperature (°C) vs. time (s) in points lying in the center of the mine area, at depths (top to bottom respectively) 0, 0.25, 0.5, 1.25 cm. The last point is within the mine.

3.2. Discussion of results

Simulations were performed in fairly realistic conditions and show that the proposed system is in fact feasible. Of course, in order to obtain more reliable performance assessment, and optimized design of the device, thorough simulation is being performed using different soil and mine parameters.

The main simplifications adopted in the case study presented are related to humidity and soil orientation and roughness. Humidity should be taken into account not only because it changes soil thermal parameters, but also because water content varies because of temperature gradients, which is described by a second differential equation, coupled with the one describing heat diffusion. In our case the simplification does not introduce as much error as it would in the case of non-localized heating. In fact, the heating/cooling process we are simulating takes place on a short time scale (minutes) so that humidity diffusion and evaporation are limited. Better accuracy could be obtained by using parameters for dryer soil in the volume over the mine, that is what can be normally expected after some time under solar heating. In any case, considering such effect would make detection easier, because the soil over the mine would normally contribute additional difference to be detected as temperature anomaly.

Orientation and roughness might affect detection when scale is comparable with that of the mine. In fact, a uniformly sloping surface would contribute a constant factor on both the energy absorbed by the soil and the apparent temperature measured by the thermometer. Both effects would be equal for soil and mine, so as to cancel. Fine roughness affects the fraction of radiated energy effectively delivered to the soil, and may contribute noise in the thermometer reading, but again the first effect partially cancels, at least as long as the same roughness is present over the mine and elsewhere. In fact this might not be the case, but as for humidity this would in most cases enhance, rather than damage, detection.

When surface changes are of the same scale as mines, they could produce false readings. Such effects can be at least partially compensated by adjusting the distance between the device and the surface e.g. using a simple set-up with a servo motor and ultrasound or infrared distance sensor.

In any case all these effects will be modeled in simulations currently being performed.

4. Extensions of the basic architecture

Up to this point no signal processing was used on measured data. In fact, performance of the system might be enhanced by post-processing, such as filtering for noise reduction, application of principal or independent component analysis, or soft computing strategies.

Other possible modifications of the system include use of a forward thermometer and of arrays of heaters and/or thermometers.

A thermometer moving before the heater would sense temperature differences caused by sun and convection before stimulation. This information could be used in two ways: the first is to estimate small space-scale variation to cancel noise due to soil variability.

The second use of a forward measurement is to make a hypothesis on the content of the volume under test, and use the sensed temperature as initial condition for a simulator just like the one we are using for the feasibility test.

Wherever simulation results yield significant difference with actual measurements, hypotheses can be changed, e.g. assuming mine parameters instead of soil. Running the simulation again would validate the hypothesis. Such prediction/correction detection scheme is in fact the object of studies being performed for a non-localized heating set-up [7-8].

In order to speed up area scanning, an array of heaters might be placed orthogonally to the scanning direction. This would result in heating of a line. At the same time, a like array of thermometers would scan the surface, obtaining information on an extended stripe of soil. Of course such a set-up requires more power than the basic one. An array of thermometers (e.g. three) could also be useful in connection with a single heater, in order to enhance detection of mines that are not situated directly under the scanning line, and to compensate for possible misalignments between heater and thermometer during scanning.

5. Conclusions

A new concept for thermal mine detection has been presented. Simulations prove feasibility of the device.

The main advantage of the approach proposed are simplicity of the device, that is based on cheap, sturdy, and easily serviceable hardware, and gives simple readings to the operator. An additional advantage is speed of area scanning, due to the fact that the process is stimulated in a rapid manner.

Intellectual property and acknowledgment

The author chose to disclose the invention described in this paper without patenting it for humanitarian reasons, and recommends those who will develop it to do likewise, reserving in any case intellectual rights on the object of this paper.

Fruitful discussion with Fernando Termentini of InterSos (Rome, Italy), Massimo Corcione and Antonio d’Alessandro of “La Sapienza” University, and Paula López Martínez of the University of Santiago de Compostela (Spain) is gratefully acknowledged. Federico Manno, Girolamo Penso, Sven Faulconer and Carlo Durastante collaborated in the simulations.

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