Inspecting Minefields and Residual Explosives by Fast Neutron Activation Method

Davorin Sudac, Slavko Majetic, Robert Kollar, Karlo Nad, Jasmina Obhodas, and Vladivoj Valkovic

Abstract—As an upgrade of a robotic mobile system for anti-personnel landmine clearance, a fast neutron probe has been considered for the detection of mines and explosive residues. Laboratory tests were made by using the 14 MeV $6 \times 10^7$ neutrons/sec beams with the associated alpha particle detection and with a LaBr$_3$ gamma-ray detector. Simulant of the anti-personnel mine was used as a target. Several measurements were made with the target buried into the soil at different depths. For each depth minimal time measurement was estimated for false negative 0.4% and false positive equal to 10%. Tests showed that it is possible to detect buried landmines as well as residual explosives; however, in order to reach the optimal speed of 10 cm/s of the demining vehicle it is necessarily to use several sealed tube neutron generators and few dozen of LaBr$_3$ gamma-ray detectors.

Index Terms—Associated alpha particle imaging, fast neutrons, land pollution, landmine detection, UNCOSS project.

I. INTRODUCTION

In the last sixty years, all around the world several millions of anti-personnel (AP) and anti-tank (AT) mines were deployed into the ground causing 2000 injuries per month, most of which (85%) were among the civilians [1]. Left after war activities, mines are still active presenting long time threats for humans and animals. Although the mine production costs only 3$, it is estimated that the localization and destruction of a single mine cost between $300 and $1,000 [2]. Landmining is usually done manually by using prodders, metal detectors and trained dogs. Special machines can be used too and in this article, the MV-4 produced by DOK-ING Ltd. is presented [3]. The MV-4 Mine Clearance System is a tracking, remotely-controlled machine designed to clear all types of the AP mines. Due to its small dimensions and maneuverability, it is suitable for demining of residential areas, forest paths, river banks and other types of terrains that are inaccessible to heavy machinery. The various operating tools for mine clearance and soil processing destroy even the smallest anti-personnel blast pressure mines and the most dangerous types of bouncing fragmentation mines. After the treatment of a minefield with such a system and in order to reach the United Nations mine clearance standard of 99.6% for humanitarian demining, it is necessary to check the minefield for the presence of explosive residues. Explosive residues are pieces of TNT fragments and AP mines as an upgrade of a robotic mobile system like MV-4 was investigated.

A. Neutron Sensors for the Detection of TNT Residues

In the past decade several neutron-based sensors was proposed to be used for landmine and unexploded ordnance (UXO) detection [4], [5]. A thermal neutron sensor was investigated for example in [6]–[8]. This technique is based on the neutron capture reaction on the $^{14}\text{N}$ nuclei, which are present in common explosive materials in a quantity much larger than in the soil. The explosive signature is given by the detection of the 10.83 MeV gamma-ray emitted in the de-excitation of the $^{15}\text{N}$ compound nucleus populated in the neutron capture reaction. Neutron back-scattering sensor was extensively researched in the framework of the EU funded project DIAMINE [9], [10], but also by other groups like in [4] and [11]. A fast neutron source like $^{232}\text{Cf}$ was used to irradiate the soil. The yield of low-energy back-scattered neutrons depends on the hydrogen content of the irradiated volume. Therefore, the explosive signature is given by the detection of the anomalous hydrogen concentrations. Pulsed fast/thermal neutron analysis (PFTNA) is a neutron-based technique which utilizes the various nuclear reactions to identify a large number of chemical elements. The basis of PFTNA is a
pulsed neutron generator utilizing the deuterium-tritium reaction $^3\text{H}(\text{d}, \text{n})^4\text{He}$. Based on this technique a portable system for landmine and UXO detection called PELAN was developed and described in [12]. The associated alpha particle imaging (API) is another technique which can be used for the TNT residue detection. Like in PFTNA the 14 MeV neutrons beam is produced in $^3\text{H}(\text{d}, \text{n})^4\text{He}$ nuclear reaction. By detecting the alpha particles it is possible to measure the time-of-flight of neutrons and to select the particular target volume for inspection [13], [14]. A large area scanning sensor for landmine detection based on API technique was studied in [15], [16], where 7 MV CN Van de Graaff accelerator was used as a source of neutrons. It has been verified that API technique improves the signal-to-background ratio in the gamma-ray spectrum by about a factor 4. Similar improvement of signal-to-background ratio was obtained in [14]. Following the encouraging results obtained there, the API technique was chosen to be the best choice for our application. In addition, due to possibility to switch off the neutron source API technique significantly reduce the problem of radiological shielding.

Fig. 2. The experimental set-up containing neutron generator ING-27, $3'' \times 3''$ LaBr$_3$ gamma-ray detector and the lead shield. To measure the DLM2.4 landmine in the soil, soil box have to be pushed to the right.

Fig. 3. The gamma-ray spectrum of the DLM2.4 landmine (black) and the gamma-ray spectrum of the soil sample (gray). Measurement time was 428 s.

Fig. 4. Three different cases studied during the measurements. Units are in millimeters.

II. MEASUREMENTS

Fig. 2 shows the experimental setup. 14 MeV neutron beam was generated by ING-27 neutron generator produced by VNIIA, Russia. Gamma rays, which were produced by the inelastic scattering of neutrons inside the target, were measured in $3'' \times 3''$ LaBr$_3$ : Ce detector. Lanthanum bromide was found to have a better energy resolution and it is twice more efficient than the sodium iodide of similar size and shape. Nine segmented alpha detectors, incorporated inside the ING-27, allows the user to tag the neutron beam and to use the associated alpha particle technique. A lead shield was placed between the gamma-ray detector and the neutron generator. Simulant of an AP mine DLM2.4 was used as a target [11]. DLM2.4 has exact chemical composition and a density like the TNT explosive. Its mass is 192.6 g; its diameter and height are respectively 80 mm and 34.5 mm. Fig. 3 shows the gamma-ray spectra of the DLM2.4 (black) and of the soil sample (gray). The carbon and
the oxygen lines are the only lines which are clearly visible. Energy cutoff was put below the 2 MeV in order to reduce the possible dead time of the electronics.

Three different cases were studied. In the first case (Fig. 4, top) DLM2.4 was buried in the level of the ground and the gamma—ray detector was as close as possible to the DLM2.4. In the second case (Fig. 4, middle) DLM2.4 was buried in the level of the ground and the distance between the DLM2.4 and the gamma-ray detector was 7 cm. In the third case gamma ray detector was as close as possible to the ground and DLM2.4 was buried 7 cm deep into the ground (Fig. 4, bottom). In all cases the soil was dry. Figs. 5–7 shows in upper position the gamma-ray spectra of the DLM2.4 in the ground for all three cases (black). Each spectrum was fitted with the assumption that it contains only carbon and oxygen contributions (gray). Contribution of the other elements like nitrogen, calcium or silicon was ignored. The fitting procedure was done by using (1) where the sum was done over the channel (ch) number.

\[ \chi^2 = \sum_{ch=ch_{\text{min}}}^{ch_{\text{max}}} \frac{(a \times \text{Carbon (ch)} + b \times \text{Oxygen (ch)} - T \text{arg et (ch)})^2}{T \text{arg et (ch)}} \]

Carbon and Oxygen are pure elemental spectra. Parameters “a” and “b” are fitting parameters called carbon content nad oxygen content, respectively. Figs. 5–7 shows in lower position the gamma-ray spectra of the soil alone (black) and the associated fitting curves (gray). The fitting results are presented in Tables I–IV. Each time the average carbon content was measured for target in/target out configurations. While the average carbon content was more or less the same, or otherwise did not depend on the time measurement, the error bar did. It became bigger as the measurement time decreases.

Fig. 8 shows the theoretical normal distributions of the carbon content in soil (top curve) and from the mine buried into the soil (bottom curve). It can be seen from the Fig. 8 that the two distributions overlap partially. Overlapping decreases as the time of measurement extends. False positive is defined by an area over the threshold of the carbon distribution in the soil. Detection probability is defined by an area over the threshold of the carbon distribution from mine buried into the soil. Threshold is defined by the formula:

\[ \text{threshold} = \text{Average background} + k\sigma_b \text{ (see Fig. 8),} \]

where parameter \( \kappa \) depends on the accepted false positive alarm rate. In this paper \( \kappa = 1.282 \) which coresponds to the 10% of the false positive.
Fig. 7. The gamma-ray spectra for the target in (top) and target out (bottom) configurations in case III. Fits are drawn with the gray color. Time window was only 6.6 ns wide. Measurement time was 417 s.

Fig. 8. The normal distribution for the carbon content in the soil and for the carbon content in TNT fragment/explosive device buried into the soil. The United Nations mine clearance standard of 99.6% in the first case was met after 15 s of the measurement, in the second case after 25 s and in the third case after 417 s. In the third case much better results were achieved by using a smaller window in the neutron time-of-flight spectrum (Fig. 9). For 6.6 ns wide time window, UN standard could be met after 140 s.

### III. SYSTEM CONFIGURATION

In order to reach the desired speed of 10 cm/s for the MV-4 demining vehicle, it is necessary to use many LaBr$_3$ gamma-ray detectors and more than one neutron generator. Possible system configuration (PSC) is shown on Fig. 10. Six neutron generators and twenty-one $\gamma$ detectors cover an area of 0.46 $\times$ 1.2 square meters. Segmented alpha detectors inside the neutron generators produce different tag neutron beams by which it is possible to find the position of the TNT residues below the PSC. If it is supposed that remotely-controlled PSC

<table>
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<th>Time (s)</th>
<th>Target in</th>
<th>Target out</th>
<th>Detection prob. (%)</th>
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<tr>
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<th>Detection prob. (%)</th>
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<td>89.3</td>
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<tr>
<td>69.5</td>
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<td>83.2</td>
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<td>60</td>
<td>0.150±0.024</td>
<td>0.098±0.024</td>
<td>80.0</td>
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some neutron techniques. For the neutron back-scattering technique, which is based on the hydrogen anomaly measurements, the small-scale variations of soil moisture content could produce false positive readings [17]. In addition, for each type of mine it is possible to define a critical value of the soil moisture for which detection is impossible. On the contrary, the presence of hydrogen in the soil, due to the moisture, seems to increase the net counts in the gamma-ray detector due to the $^{14}$N($n, \gamma$) capture reaction on the explosive material, demonstrating that soil moisture has the opposite effect on the thermal neutron sensor [8].

We believe that by multiple scanning of the minefield with MV-4 and PSC, the soil moisture influence can be put to the acceptable level, because only the TNT fragments which are close to the surface are detected in most cases.

IV. CONCLUSION

A fast neutron interrogation system for detection of AP mines and small pieces of TNT left after landmine clearance by MV-4 machine was investigated. TNT fragments and AP mines could be detected by using the 14 MeV neutron beam and the associated alpha particle technique. It has been shown that the carbon content, which is much higher in the TNT explosive than in the soil, can be used as TNT signature. The active “width” of the PSC is 1.2 m and inspecting 46 cm every 15 seconds corresponds to an equivalent speed of 3 cm/s, which is three times less than the desired one. Nevertheless, from a physical point of view the higher speed could be achieved by using more than one PSC.

Although the soil moisture influence has not been studied in this paper it is known that soil moisture can significantly impact

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REFERENCES
