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Landmine-identification system based on the detection of scattered neutrons: A feasibility study

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ABSTRACT

The feasibility study of the landmine identification system (LIS) based on the angular distribution of thermal neutrons for buried landmines was undertaken in this work. The operation of the system was based on both artificial neural networks (ANN) and least-squares methods in which the input data were prepared by the MCNP6.1 Monte Carlo code before feeding into MATLAB and dedicated programs, respectively. Having achieved the promising ANN and least-squares results (with a relative error of less than 15%), the study confirmed that the proposed system is sensitive to the depth of the landmine as well as to the soil moisture, therefore it could be used for landmine identification.

1. Introduction

Unidentified buried landmines are among the major unresolved problems in the countries with a post-war history. According to various expert estimations, it is known that more than 80 million landmines, shells, and other explosive devices of various types are still buried in different countries worldwide [Tbarki et al., 2021]. This number is constantly changing due to local military conflicts and it is a serious problem for the state security agencies of these countries.

There are several classic methods such as using trained animals or metal detectors for landmine identification. However, locating landmines using these methods is a costly, dangerous, and time-consuming task. In addition, some techniques such as those using metal detectors are effective identification methods only for explosive devices containing major metallic parts and unsuitable for plastic explosives.

New advanced methods for detecting explosive devices, such as electromagnetic detection, [Stanley et al., 2002], biological [Habib, 2007], and nuclear methods [Kiraly et al. 2001; Bagdasaryan et al., 2015; Metwally, 2015; Han et al., 2019; Han et al., 2021; Bishnoi et al., 2019; Pino et al., 2021; Xue et al., 2020] are currently being developed and implemented.

The detection of explosives using nuclear methods has been widely studied recently. Neutron methods can be used based on the fact that landmine explosives (TNT ($C_7H_5N_3O_6$), RDX ($C_3H_6N_6O_6$), and hexogen ($O_8N_8C_4H_8$)) are composed of elements with low and medium atomic mass, and different from the compositions of soil (dry soil: O (51.4%), Na (0.614%), Mg (1.31%), Al (6.87%), Si (27.06%), K (1.43%), Ca (5.11%), Ti (0.46%), Mn (0.072%), Fe (5.64%), and modified compositions according to various moistures) and most common organic materials, which allow them to be identified.

Among different nuclear methods, those based on neutrons can effectively detect explosives, even if they are buried under a relatively thick layer of soil due to the high penetrating power of neutrons. The well-known, conventional neutron methods with wide practical applications use two different approaches: (1) neutron activation of target elements [Takahashi et al., 2011; Bagdasaryan et al., 2015; Yoshikawa et al., 2009; Elsheikh, 2018; McFee et al., 2013; Takahashi et al., 2010] and/or (2) neutron scattering [ElAgib et al., 2009; Kiraly et al., 2001; Drosg and Brooks, 2005; Masoudi and Ghashami, 2014; Metwally, 2015; Elsheikh et al., 2012; Xue et al., 2020].

The prompt gamma-ray neutron activation analysis (PGNAA) including the neutron-induced gamma-rays from (n, γ) and (n, n'γ) reactions in hydrogen (2.2 MeV), oxygen, carbon, and nitrogen (6, 4.4 and 10.8 MeV) are used for the explosive detection. In most cases, the activation systems are not portable and are usually installed at customs terminals.

In the second approach, the neutron scattering/backscattering used for the explosive detection [ElAgib et al., 2009; Elsheikh et al., 2012;

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Datema et al., 2001] consists of the registration of thermal neutrons backscattered from the soil. This method is widely used because the probability of the backscattered neutrons from hydrogen (depending on the explosive type, the atomic fraction of hydrogen is about 30%) is one order of magnitude higher than the probability of 10.8 MeV gamma-ray production from nitrogen. However, this approach is most suitable for identifying buried landmines in relatively dry soils, as well as for the landmines and casings containing a sufficient amount of hydrogen, otherwise, the identification fails by increasing the soil moisture. However, some landmine identification efforts with tagged neutrons [Han et al., 2019; Valkovic et al., 2013; Valkovic et al., 2010] have yielded satisfactory results even in dense medium with strong interference substances.

Having undertaken successful studies on the angular distribution of thermal neutrons surrounding a soil sample to estimate the soil moisture [Ghaemifard et al., 2020; Bedenko et al., 2021], it has been decided to use a similar scenario for landmine identification.

Different conditions for the depth of the landmines as well as the soil moisture have been considered. To this purpose, the response of a single thermal neutron detector located at different angles around the buried landmine region and exposed to an easily-available ^{241}Am-Be neutron source has been simulated using the MCNP6.1 code [Goorley et al., 2012] which is reported in Section 2.1. The detector responses for different conditions form a data matrix that is used further as input data for both the artificial neural networks (ANN) computations with MATLAB and least-squares analyses explained in Section 2.2. The landmine identification system (LIS) results as well as the identification thresholds are presented in Section 3. Section 4 presents a few suggestions for future works.

2. Materials and methods

2.1. Conceptual design of angular distribution of thermal neutrons system

As explained, a new landmine identification approach has been proposed based on the angular distribution of thermal neutrons registered by a detector array. Both the ANN and the least-squares analyses have been used to determine the depth of the landmine after its presence is confirmed. The proposed LIS requires a Monte Carlo-generated data library for the so-called known landmine depth and X-position. However, it should be noted that since soil moisture can disturb the performance of the system, different soil moistures have been considered for the simulations. The landmine size is also an important factor in the process, but to avoid the complexities, it has been decided to fix the size at this present stage.

The anti-personal landmines are generally composed of explosive material (*i.e.*, TNT or $C_6H_2(NO_2)_3CH_3$) made of hydrogen, carbon, oxygen, and nitrogen with 1.65 g/cm^3 density, whilst hydrogen, carbon, and oxygen are the main constituents of the enclosure (Lucite in this study with the chemical formula of $C_5O_2H_8$ and density of 1.19 g/cm^3) [McConn et al., 2011]. The cylindrical-shaped landmine in this work has a radius and a height of 3.5 cm and 2.2 cm, respectively, surrounded by a 6-mm thick layer of Lucite.

The neutron source is an important component of all explosive-detection systems based on neutron interactions. Isotopic (α-n) sources such as Am-Be type [Ghal-Eh et al., 2019], as well as neutron generators (D-D (E_n = 2.45 MeV) and D-T (E_n = 14.1 MeV)) are the conventional neutron sources in such systems.

In this work, an assembly consisting of five AmO_2-Be capsules of Amersham X. 14 (code AMN.25) with the compositions summarized in Table 1, representing a stable neutron flux (with a total intensity of 1.143 × 10^8 n/s) [Bedenko et al., 2020]) for a very long time with the least contamination of gamma-rays, has been used [Amersham/Searle, 1976].

Table 1
Compositions of the active part of a homogenized Amersham X.14 capsule.

Nuclide	Isotopic abundance [%]	Nuclide mass fraction [%]	Nuclide density [(b·cm)$^{-1}$]	Mass [g]
^{9}Be	1.00E+00	9.26E-01	1.13E-01	4.60E+01
^{16}O	9.98E-01	8.70E-03	4.81E-05	4.33E-01
^{17}O	3.80E-04	3.52E-06	1.83E-08	1.75E-04
^{18}O	2.05E-03	2.01E-05	9.88E-08	1.00E-03
^{241}Am	9.46E-01	6.22E-02	2.28E-05	3.09E+00
^{242}Am	3.60E-02	2.37E-03	8.67E-07	1.18E-01
^{243}Am	1.79E-02	1.19E-03	4.32E-07	5.90E-02

Note should be taken that the activity of one capsule of Amersham X.14 (code AMN.25) is 370 GBq (10 Ci), according to its experimentally measured intensity [Marsh et al., 1995], is 2.126 × 10^7 n/s in 4π geometry. The MAximum Dose Equivalent (MADE) in the ICRU sphere, calculated using conversion factors from [ICRP, 1982], is 372 pSv × cm^2. The calculated unmoderated neutron yield used in this simulation and the conversion factors from spectrum to effective equivalent dose, respectively, are 2.285 × 10^7 n/s and 1.615 μSv × h^{-1}/(n/(s. cm^2)) [Bedenko et al., 2021], respectively.

The capsule shell material is stainless steel (SUS316L) with the following compositions (wt. %): C - 0.08; Si - 1.0; Mn - 2; P - 0.045; S - 0.03; Ni - 10; Cr - 17.00; Mo - 2.5; the rest is Fe.

Fig. 1 also shows the configuration of a cylindrical collimator to generate a narrow beam of neutrons with the required neutron spectrum for the effective detection of explosives. The collimator material is high-density borated polyethylene of the following composition (wt. %): H - 12.7; B - 4.69; C - 72.3; O - 10.3. Having considered the fine-powder structure of the active part of the capsule, the calculated neutron spectrum of the Amersham X.14 capsule and its geometric model for the MCNP6.1 code are taken from [Bedenko et al., 2021] (Fig. 2). The neutron source density calculation was performed in the Nedis-2m program code [Vlaskin, 2006; Vlaskin and Khomyakov, 2021] taking into account the anisotropy of neutron emission (α, n)-reactions for specific levels of residual nuclei (evaluated and implemented into the program library by the developers based on available experimental data), and using data from [Murata et al., 2006] three-body reaction channel ^{9}Be(α,n)3^{4}He [Murata et al., 2006]. Taking into account the anisotropy of neutron emission, the (α,n)-reaction in Be will make it possible to obtain more accurate values of the dose coefficient of the leakage neutron spectrum, which can be used to determine the dose rate. This will allow optimizing the size and weight of the biological protection shield against neutron radiation.

A distinctive feature of the proposed approach is the use of a thermal neutron detector of commercially available cylindrical proportional BF_3 counter (LND20137 [LND, 2022]) (See Table 2). Three detectors in different positions (position num. 1, 10, and 19 as shown in Fig. 3) have been moved in such a way to cover 26 different angles. Since considering either one movable detector in 26 positions or, 26 fixed detectors in each position is inefficient, three detectors have been selected to scan all 26 positions. This detectors array allows obtaining detailed information on the angular distribution of thermal neutrons scattered off and leaving the surface of landmine-containing soil. The (n, α) reaction rate in ^{10}B nuclei of the BF_3 counter is considered as the simulation response of the detector.

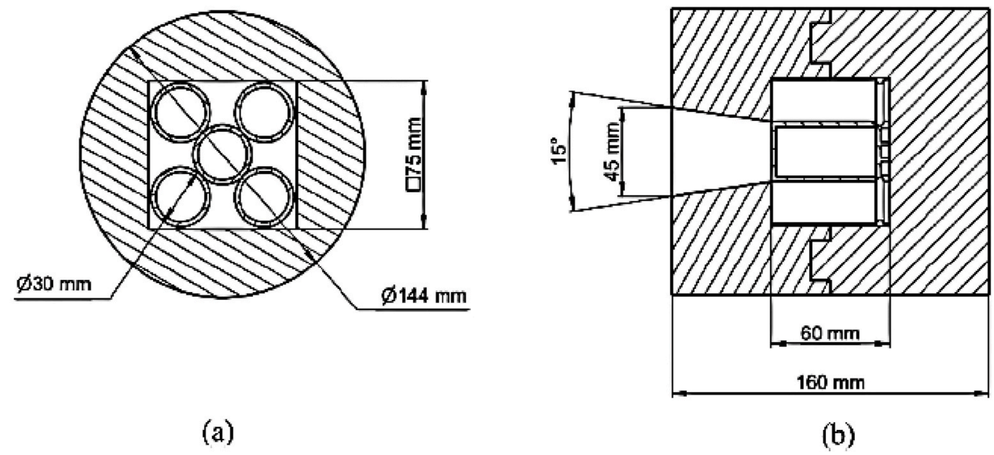

Fig. 1. Neutron source assembly and proposed collimator. (a) Upper and (b) Sectional views.

2.2. Least-squares analysis

Least-squares analysis refers to a method in which a set of given input data with specific labels are compared with a so-called unknown one (with an unknown label) by summation over squared difference values to determine which input data is the nearest one to the unknown data, and therefore, the most appropriate label of the unknown data is obtained.

In this study, using the Monte Carlo MCNP6.1 code, the responses of the thermal neutron detector located at 26 different locations above the landmine-containing soil are calculated to be taken as input data. Having considered five different landmine depths (0, 5, 10, 15, and 20 cm, which are the labels in least-squares analysis) as the reference library data, the 26 × 5 response matrix has been generated. The soil containing an unknown-depth (*i.e.*, the unknown label) landmine when irradiated by neutrons results in 26 detector responses (X_i, $i = 1, \ldots, 26$). The X values are compared with all columns of the response matrix using the least-squares formula of Eq. (1).

$$\chi_j^2 = \sum_{i=1}^{26} \left(X_i - Y(j)_i\right)^2 \left(\mathrm{j} = 1, \ \ldots, \ 5\right) \quad (1)$$

where, $Y(j)_i$ is the response of the i-th detector when the landmine is located at the j-th depth. The χ_j^2 are calculated for all landmine depths (*i. e.*, j values), and the two lowest χ_j^2 values, corresponding to $j_<$ and $j_>$, are identified. One may conclude that the unknown spectrum (X) is related to the known spectra (Y), following the linear superposition of Eq. (2):

$$X = PY(j_<) + QY(j_>) \quad (2)$$

where coefficients P and Q determine the contributions of the two most similar spectra to the unknown spectrum ranging from 0 to 1. The unknown depth is therefore calculated as:

$$Landmine\ depth = P \times Depth\ (j_<) + Q \times Depth(j_>) \quad (3)$$

2.3. ANN

ANN is designed to behave like interconnected neuron cells in the brain without being programmed according to task-specific rules. A neural network is a group of neurons with special connections from one point to another point of the network which have identical functions,

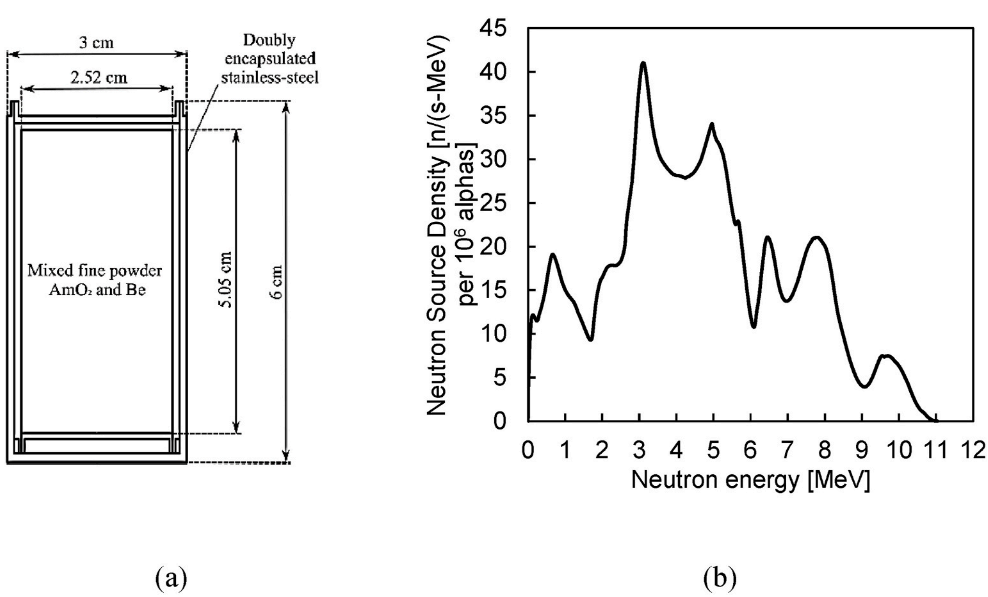

Fig. 2. Amersham X.14 AmO_2-Be neutron source used in the simulation. (a) 3D model, (b) Neutron spectrum in the internal volume of the capsule.

Table 2
Main characteristics of the LND20137 proportional counter [LND, 2022].

General specifications	Value
Maximum length [mm]	123.8
Maximum diameter [mm]	16
Effective length [mm]	50.8
Effective diameter [mm]	15.49
Gas pressure [atm.]	0.53
Enrichment for isotope ^{10}B [%]	96

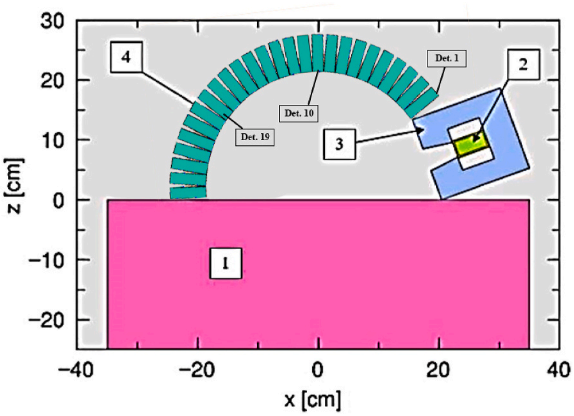

Fig. 3. Simulation setup: (1) Soil, (2) Neutron source, (3) Collimator, and (4) Different detector locations.

but in various sizes and shapes depending on their positions in the neural system.

In the present study, to estimate the landmine depth, the datasets generated by MCNP6.1 have been used as inputs of the ANN toolbox of MATLAB, called *nntool* [MATLAB, 2019]. Basically, to train the network and achieve a reasonably small relative error, a large data library is required. Herein, similar to the least-squares method, the calculated responses of the thermal neutron detectors in 26 angles for five different landmine depths (*i.e.*, from 0 to 20 cm) in the form of 26 × 5 response matrix are used for the network training. The ANN performance can be monitored by comparing the ANN response and true values from control data which were randomly chosen. In *nntool*, having chosen the Feed-forward Backprop ANN type, the ANN details have been summarized in Table 3 and illustrated in Fig. 4.

3. Results and discussion

In order to justify the presence of the landmine, the proposed LIS has been moved over the suspected region along the X-axis and the corresponding detector responses are simulated with the MCNP6.1 code. Different soil moisture percentages (*i.e.*, 0, 5, 10, 15, and 20%) have been considered to check the sensitivity of the LIS.

First, to determine the soil moisture threshold to achieve acceptable accuracy, the X coordinate of the landmine, the soil moisture, and the landmine depth are varied. Different statistical descriptive parameters

Table 3
ANN specifications used in MATLAB's *nntool*.

ANN specifications	Value
Number of input/output data	26, 1
Hidden layer, Number of neurons	Tansig, 20
Output layer, Number of neurons	Purelin, 1
Training function	TRAINGDX
Adaption-learning function	TRAINLM
Performance function	MSE

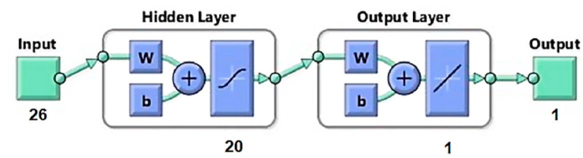

Fig. 4. A double-layer neural network design for estimating unknown landmine depth.

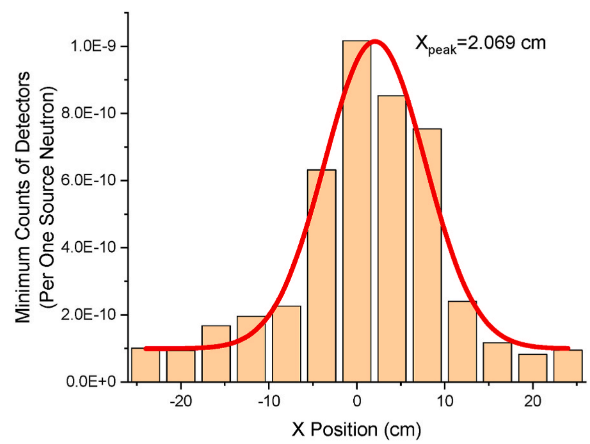

Fig. 5. The minima of detector responses when the LIS is displaced over the surface (from X = −24 cm to X = 24 cm) where the landmine is located at X = 0 cm. The landmine depth and soil moistures are 0 cm and 0%, respectively.

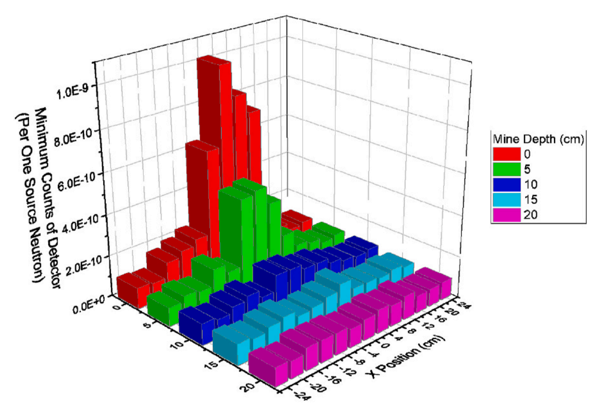

Fig. 6. Variation of landmine depth from 0 up to 20 cm (The landmine is buried in dry soil and at X = 0 cm). The landmine location is obtained by calculating the peak position of the minimum response. As the landmine depth increases, the peak in the histogram tends to disappear, and therefore the identification of landmine location becomes difficult.

Table 4
Operational landmine depths and soil moisture percentages of the proposed LIS. Passed and failed are corresponding to the performance errors of less and greater than 4 cm in locating the landmine.

		Soil Moisture (%)				
		0	5	10	15	20
Landmine depth (cm)	0	Passed	Passed	Passed	Passed	Passed
	5	Passed	Passed	Failed	Failed	Failed
	10	Passed	Failed	Failed	Failed	Failed
	15	Passed	Failed	Failed	Failed	Failed
	20	Failed	Failed	Failed	Failed	Failed

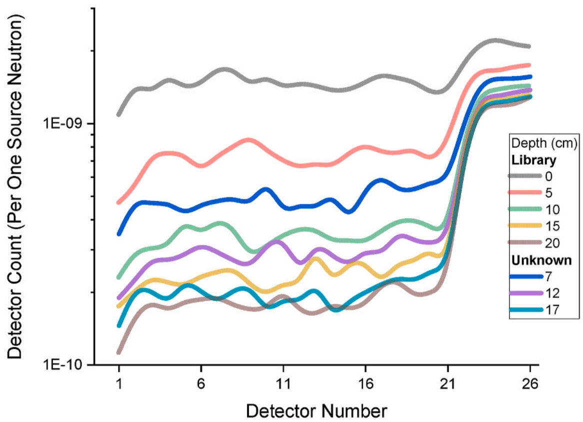

Fig. 7. The responses of 26 thermal neutron detectors when the landmine is buried in different depths of dry soil.

Table 5
The landmine depth estimation by ANN and least-squares methods.

		Unknown Mine Depth [cm]		
True Values		7	12	17
Estimated Values	Least Squares Method [% Rel. Err.]	8.035 (14.79)	12.460 (3.83)	17.830 (4.88)
	Artificial Neural Networks Method [%Rel. Err.]	6.464 (7.66)	13.471 (12.26)	16.196 (4.73)

Note should be taken that since the neutron source strength used in this study is 1.143×10^8 n/s, one may expect that every 40 cm × 40 cm of the field is swept in 35 s, which is equivalent to about 4 min for each square meter. However, the sweeping time can be reduced by increasing the neutron yield.

have been studied such as the mean, standard deviation, maximum, and minimum of the 26 detector responses. It has been realized that the best parameter for the identification of the landmine location in this study is the minimum response of thermal neutron detectors that can be placed at 26 different angles. As seen in Fig. 5, the fitted Gaussian function to the histograms of the minimum responses shows that the LIS can determine the landmine location with about 2 cm error when the soil moisture and landmine depth are 0% and 0 cm, respectively.

As the landmine depth increases, the accuracy of the LIS deteriorates. This can be seen in Fig. 6, where the landmine depth is varied from 0 up to 20 cm. It should be noted that, as far as the literature survey confirms, the maximum landmine depth is about 15 cm. The soil moisture also has a disturbing effect on the LIS performance. As summarized in Table 4, the LIS may be used only in some landmine depths and soil moistures. The rejection criterion is that the system is unable to locate the landmine with less than 4 cm accuracy.

Having discussed the details of ANN and least-squares methods in landmine depth determination, both the library (*i.e.*, 0, 5, 10, 15, and 20 cm depths) and unknown responses (*i.e.*, 7, 12, 17 cm depths) to different landmine depths have been simulated with the MCNP6.1 (See Fig. 7). The number of neutrons used in each simulated response is 2E9 which keeps the uncertainties well below 5%. As can be seen in Fig. 7, the detector responses for different landmine depths are well separated which is an important feature for both ANN and least-squares methods. Besides, the relatively large responses of the detectors at positions 21 and higher may be attributed to the large probability of near-to-forward neutron scatterings. Table 5 summarizes the ANN and least-squares results, where it can be seen that the landmine depth can be recognized with an appropriate working precision. The relative errors in these two methods are less than 15% which enables the proposed system to guess the initial depth of the existing landmine before the procedure for finding and removing the landmine is followed.

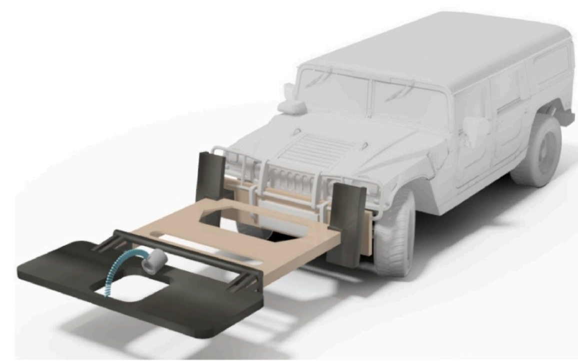

Fig. 8. Conceptual schematic view of the LIS installed on a military vehicle.

Moreover, the contribution of gamma-rays in the detector counts can be ignored since the low-amplitude region of the BF_3 spectrum which is corresponding to the electronic noise and gamma-rays can be easily discriminated by an appropriate lower-level discrimination setting of the data acquisition electronics.

4. Conclusions

A LIS based on the angular distribution of thermal neutrons has been proposed in this study. The system includes thermal neutron detectors and a collimated AmO_2-Be neutron source which aims, with the help of ANN and least-squares methods, to identify the presence of the commonly-used landmines and their depths in the soil. However, similar to other neutron-based devices, the proposed LIS exhibits its best performance in dry-soil fields.

Although the present LIS requires the registration of the detector counts at 26 different angles, it is anticipated that the use of a precision rotating arm may reduce the number of thermal neutron detectors to only three.

In addition, the proposed LIS is portable and can be adapted to medium-duty civil and military vehicles. Unlike D-D and D-T neutron generators, the proposed installation generates a stable neutron flux for a long time and does not require highly qualified personnel for autonomous operation under special conditions.

The system itself, with the necessary equipment, electronics, and biological protection shielding, can be built into the front side of an armored truck (see Fig. 8), the second escort armored car is used to transport Am-Be capsules in standard shipping containers from the manufacturer as a biological protection unit when the LIS is not under operation. The modified truck will increase the mobility of the system under study and will speed up the time for preliminary assessment of the terrain.

The proposed LIS system consists of five highly active AmO_2-Be capsules with a total activity of 1.85×10^3 GBq and intensity $I_n = 2.126 \times 10^7 \times 5 = 1.063 \times 10^8$ n/s [Marsh et al., 1995]. It is obvious that a simple radiation shield such as a boron-containing polyethylene block surrounding this assembly to minimize the neutron flux, as well as the ambient absorbed dose to the maximum permissible values, will have very large dimensions which is inefficient. Therefore, the development of a small-sized multi-layered protective shield against gamma-rays and neutrons to effectively slow down the fast as well as to absorb scattered thermal neutrons and gamma-rays is being investigated for future works in parallel with the possible modification of the vehicle for the installation studied in this study.

As already mentioned in Section 2, soil moisture and landmine depth were the two variables studied in the present work. However, a similar scenario may apply to the landmine size which is being investigated by authors.

Credit author statement

In this paper the contribution of each author is the following: ***Faezah Rahmani***: Conceptualization, Validation, Formal analysis, Software, Writing. ***Nima Ghal-Eh***: Methodology, Conceptualization, Software, Writing ***Sergey V. Bedenko***: Conceptualization, Software, Visualization, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Amersham/Searle, 1976. Neutron sources ^{241}Am-Be and ^{252}Cf. Tech. Bull. 76–77.

Bagdasaryan, K.E., Batyaev, V.F., Belichenko, S.G., Bestaev, R.R., Gavryuchenkov, A.V., Karetnikov, M.D., 2015. Parameters of explosives detection through tagged neutron method. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 784, 412–416.

Bedenko, S.V., Vlaskin, G.N., Ghal-Eh, N., Lutsik, I.O., Irkimbekov, R., Rahmani, F., Vega-Carrillo, H.R., 2020. Nedis-Serpent simulation of a neutron source assembly with complex internal heterogeneous structure. Appl. Radiat. Isot. 160, 109066.

Bedenko, S.V., Ghal-Eh, N., Kuskov, V.A., Vega-Carrillo, H.R., Vlaskin, G.N., 2021. Neutron beam preparation for soil moisture measurements: Nedis-PHITS and artificial neural networks study. Appl. Radiat. Isot. 172, 109688.

Bishnoi, S., Thomas, R.G., Sarkar, A., Sarkar, P.S., Sinha, A., Saxena, A., Gadkari, S.C., 2019. Modeling of tagged neutron method for explosive detection using GEANT4. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 923, 26–33.

Datema, C.P., Bom, V.R., van Eijk, C.W., 2001. Landmine detection with the neutron backscattering method. IEEE Trans. Nucl. Sci. 48 (4), 1087–1091.

Drosg, M., Brooks, F.D., 2005. Increasing the capability of MNBRP for the detection of anti-personnel landmines. Appl. Radiat. Isot. 63 (5–6), 599–605.

ElAgib, I., Elsheikh, N., AlSewaidan, H., Habbani, F., 2009. Monte-Carlo simulations of elastically backscattered neutrons from hidden explosives using three different neutron sources. Appl. Radiat. Isot. 67 (1), 39–45.

Elsheikh, N.A., 2018. Monte Carlo modelling of a neutron-induced gamma-ray sensor for landmine or explosive detection. J. Radiat. Res. Appl. Sci. 11 (4), 403–407.

Elsheikh, N., Viesti, G., ElAgib, I., Habbani, F., 2012. On the use of a (^{252}Cf-^{3}He) assembly for landmine detection by the neutron back-scattering method. Appl. Radiat. Isot. 70 (4), 643–649.

Ghaemifard, M., Ghal-Eh, N., Najafabadi, R.I., Vega-Carrillo, H.R., 2020. Angular distribution of scattered neutrons as a tool for soil moisture measurement: a feasibility study. Appl. Radiat. Isot. 160, 109131.

Ghal-Eh, N., Rahmani, F., Bedenko, S.V., 2019. Conceptual design for a new heterogeneous ^{241}Am-^{9}Be neutron source assembly using SOURCES4C-MCNPX hybrid simulations. Appl. Radiat. Isot. 153, 108811.

Goorley, T., James, M., Booth, T., Brown, F., Bull, J., Cox, L.J., Durkee, J., Elson, J., Fensin, M., Forster, R.A., Hendricks, J., 2012 Dec 1. Initial MCNP6 release overview. Nucl. Technol. 180 (3), 298–315.

Habib, M.K., 2007. Controlled biological and biomimetic systems for landmine detection. Biosens. Bioelectron. 23 (1), 1–18.

Han, M.C., Jing, S.W., Gao, Y.D., Guo, Y., 2019. Experiment and MCNP simulation of a portable tagged neutron inspection system for detection of explosives in a concrete wall. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 929, 156–161.

Han, M.C., Jing, S.W., Gao, Y.D., 2021. Simulation and data analysis of a portable tagged neutron system for detection of explosives hidden in packages. Radiat. Phys. Chem. 182, 109361.

International Commission on Radiological Protection. Committee 3, 1982. Protection against Ionizing Radiation from External Sources Used in Medicine: A Report of Committee 3 of the International Commission on Radiological Protection, vol. 1. Pergamon Press.

Kiraly, B., Olah, L., Csikai, J., 2001. Neutron-based techniques for detection of explosives and drugs. Radiat. Phys. Chem. 61 (3–6), 781–784.

LND, 2022. Cylindrical BF_3 Neutron Detectors. LND, INC. Reviewed on January 2022]. https://www.lndinc.com/products/neutron-detectors/20137.

Marsh, J.W., Thomas, D.J., Burke, M., 1995. High resolution measurements of neutron energy spectra from Am-Be and Am-B neutron sources. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 336, 340–348.

Masoudi, S.F., Ghashami, M., 2014. D-T neutron generators as a feasibility tool for landmine detection based on neutron backscattering method. Ann. Nucl. Energy 65, 441–445.

McConn, R.J., Gesh, C.J., Pagh, R.T., Rucker, R.A., Williams III, R., 2011. Compendium of material composition data for radiation transport modeling (No. PNNL-15870 Rev. 1). Pacific Northwest National Lab.(PNNL). Richland, WA (United States).

McFee, J.E., Faust, A.A., Andrews, H.R., Clifford, E.T.H., Mosquera, C.M., 2013. Performance of an improved thermal neutron activation detector for buried bulk explosives. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 712, 93–101.

Metwally, W.A., 2015. Multi-parameter optimization of a neutron backscattering landmine detection system. Appl. Radiat. Isot. 105, 290–293.

Murata, T., Matsunobu, H., Shibata, K., 2006. Evaluation of the (α, xn) Reaction Data for JENDL/AN-2005 (No. JAEA-RESEARCH–2006-052). Japan Atomic Energy Agency.

Pino, F., Fontana, C.L., Nebbia, G., Pedersen, B., Varasano, G., Sardet, A., Carasco, C., Pérot, B., Sebert, A.G., Poli, J.P., Sannié, G., 2021. Detection module of the C-BORD rapidly relocatable tagged neutron inspection system (RRTNIS). Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 986, 164743.

Stanley, R.J., Gader, P.D., Ho, K.C., 2002. Feature and decision level sensor fusion of electromagnetic induction and ground penetrating radar sensors for landmine detection with hand-held units. Inf. Fusion 3 (3), 215–223.

Takahashi, Y., Misawa, T., Masuda, K., Yoshikawa, K., Takamatsu, T., Yamauchi, K., Yagi, T., Pyeon, C.H., Shiroya, S., 2010. Development of landmine detection system based on the measurement of radiation from landmines. Appl. Radiat. Isot. 68 (12), 2327–2334.

Takahashi, Y., Misawa, T., Pyeon, C.H., Shiroya, S., Yoshikawa, K., 2011. Development of land mine detector system based on the measurements of capture γ-rays with anticoincidence and coincidence methods. J. Nucl. Sci. Technol. 48 (1), 31–38.

Tbarki, K., Ksantini, R., Ben Said, S., Lachiri, Z., 2021. A novel landmine detection system based on within and between subclasses dispersion information. Int. J. Rem. Sens. 42 (19), 7405–7427.

MATLAB, 2019 The MathWorks, Inc., Natick, Massachusetts, United States.

Valkovic, V., Sudac, D., Matika, D., 2010. Fast neutron sensor for detection of explosives and chemical warfare agents. Appl. Radiat. Isot. 68 (4–5), 888–892.

Valkovic, V., Sudac, D., Obhodas, J., Eleon, C., Perot, B., Carasco, C., Sannié, G., Boudergui, K., Kondrasovs, V., Corre, G., Normand, S., 2013. The use of alpha particle tagged neutrons for the inspection of objects on the sea floor for the presence of explosives. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 703, 133–137.

Vlaskin, G.N., 2006. NEDIS2. 0 Code for Calculating the Neutron Yield and Spectra from. Reactions on the Nuclei of Light Elements and Owing to Spontaneous Fission. Preprint VNIINM, 06-1.

Vlaskin, G.N., Khomyakov, Y.S., 2021. (α, n) Neutron spectra on thick light targets. Atomic Energy 130 (2), 104–118.

Xue, H., He, D.D., Gong, K., Jing, S.W., Zheng, Y.L., 2020. Design and simulation of landmines detection system based on fast neutron analysis. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 482, 82–87.

Yoshikawa, K., Masuda, K., Takamatsu, T., Yamamoto, Y., Toku, H., Fujimoto, T., Hotta, E., Yamauchi, K., Ohnishi, M., Osawa, H., Shiroya, S., 2009, March. Results of the development of humanitarian landmine detection system by a compact fusion neutron source and dual sensors. AIP Conf. Proc. 1099 (No. 1), 652–655. American Institute of Physics.