A MULTISIGNAL DETECTION OF HAZARDOUS MATERIALS FOR HOMELAND SECURITY

by

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The detection of hazardous materials has been identified as one of the most urgent needs of homeland security, especially in scanning cargo containers at United States ports. To date, special nuclear materials have been detected using neutron or gamma interrogation, and recently the nuclear resonance fluorescence has been suggested. We show a new paradigm in detecting the materials of interest by a method that combines four signals (radiography/computer tomography, acoustic, muon scattering, and nuclear resonance fluorescence) in cargos. The intelligent decision making software system is developed to support the following scenario: initially, radiography or the computer tomography scan is constructed to possibly mark the region(s) of interest. The acoustic interrogation is utilized in synergy to obtain information regarding the ultrasonic velocity of the cargo interior. The superposition of the computer tomography and acoustic images narrows down the region(s) of interest, and the intelligent system guides the detection to the next stage: no threat and finish, or proceed to the next interrogation. If the choice is the latter, knowing that high *Z* materials yield large scattering angle for muons, the muon scattering spectrum is used to detect the existence of such materials in the cargo. Additionally, the nuclear resonance fluorescence scan yields a spectrum that can be likened to the fingerprint of a material. The proposed algorithm is tested for detection of special nuclear materials in a comprehensive scenario.

Key words: nuclear material detection, cargo scanning, multiple signals, fuzzy logic, intelligent decision

INTRODUCTION

The detection of hazardous materials hidden in cargo containers is a major challenge. The import of special nuclear materials convertible to weapons represents potentially a very significant threat. The annual number of cargo containers reaching United States ports and entry points exceeds six million. A manual search of all is impossible. Furthermore, lengthy staying of cargo at entry points has an impact on the country's market and economy. On the other hand, manual inspection of randomly selected containers reduces the reliability and trustworthiness of customs.

The need for fast and reliable inspection of containers led to the development of a first barrier of defense to nuclear threats. Several methods for cargo interrogation and screening have been developed: conventional X-ray tomography and computer tomography (CT) reconstruction [1], neutron [2], gamma [3], acoustic interrogation [4], and muon scattering tomography [5]. Only a small fraction of cargo is singled out for further manual search which reduces time requirements by several orders of magnitude for the entire screening process. The limitations (time, cost of the equipment, detection accuracy) of current technology still impose high scanning costs during long scanning times. In addition, the rise of annual global trade rate

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demands the improvement of inspection time while maintaining high levels of detection accuracy.

We propose a new detection algorithm that applies fuzzy logic tools [6] on scanning data and indicates the necessity for further manual search. A test case for the detection of special nuclear materials (SNM) is presented and discussed. Future improvement of the presented methodology is outlined.

MULTISIGNAL DETECTION METHODOLOGY

General characteristics

The proposed detection algorithm uses the combination of four signals to detect the presence of SNM in cargo interiors. The primary goal is the identification of cargo content by marking the regions of interest (ROI) defined as high atomic number (high *Z*) material regions. By combining data obtained from the conventional radiography/CT scanning, acoustic interrogation, muon scattering detection, and nuclear resonance fluorescence (NRF), the proposed methodology offers a new decision making process to be used for cargos. Flexible and powerful tools of fuzzy logic allow for an intelligent decision on whether the container merits for manual search or not.

The main purpose of the developed four-signal detection algorithm is to exploit the unique characteristics of each signal, and fuse them raising the overall efficiency in finding the SNM. The intelligent processing offers an automated procedure for extracting valuable information with online decision making. The superposition of signal features and fuzzy methods promotes the accurate and quick detection of SNM.

Radiography/CT scanning

High speed moving electrons that collide with a metal produce X-rays. Kinetic energy, see (1), of electrons is transformed into electromagnetic. A common method to produce X-rays is through bremsstrahlung radiation

$$KE \quad \frac{1}{2}mv^2 \tag{1}$$

In this case the electrons approach the target nucleus and are influenced by a nucleus force much stronger than the attractive electrostatic force. As the electrons pass by the target, they lose some of their kinetic energy and are slowed down. The resulting radiation, from the slowing down of electrons, is bremsstrahlung photons. The advantage is that none of the photons has more energy, see (2), than the electrons had to begin with

$$E \quad hv \tag{2}$$

where $h \quad 4.14 \;\; 10^{15}$ eVs is the Planck's constant. The X-ray beam produced from bremsstrahlung is polychromatic (photons with different energies making up a spectrum).

X-ray cargo inspection is done by highly energetic X-rays. The absorption of X-rays depends on the penetrated material atomic number *(Z* number) and is modelled from the attenuation law as in eq. (3) for one penetrated material

$$N(x) \quad N \;\; \exp(\;\; \mu\Delta x) \tag{3}$$

where N is the initial number of photons and μ is the absorption coefficient which depends on the material properties and incident photon energy. Increasing the Z number denotes increasing the absorption capability. As a result, detectors show the images based on penetrating properties of materials. Radiographic images are used in synergy with the computer tomography scanning to represent containers in three dimensions. This is possible by the subdivision of the container into voxels and the use of Hounsfield units (arbitrary comparison unit to water absorption) to assign greyscale values to voxels. Radiography/CT qualifies as a non-destructive method for sealed containers. At the same time, fast screening is provided while the cost of utilization remains low. The presence of high Z material is indicated, and the respective area is marked as a ROI.

Acoustic scanning

Acoustic scanning takes advantage of the ultrasonic properties of the materials under investigation. Ultrasonic is the sound pressure with frequencies more than that of human hearing. This type of scanning is based on mechanical wave (longitudinal) propagation as is presented in wave equation

$$\frac{\partial^2 u}{\partial t^2} \quad c^2 \frac{\partial^2 u}{\partial x^2} \tag{4}$$

where c represents the phase velocity. In case of the longitudinal waves, the wave equation gets the form of eq. (5)

$$\frac{\partial^2 y}{\partial t^2} \quad \frac{B}{\rho_0} \frac{\partial^2 y}{\partial x^2} \tag{5}$$

where y is the displacement, ρ_0 – the undisturbed equilibrium density of the medium, and B – the adiabatic bulk modulus of elasticity, eq. (6)

$$B \quad \rho_0 \frac{\mathrm{d}P}{\mathrm{d}\rho} \tag{6}$$

where dP is the change in the pressure from the equilibrium state, and dρ is the change in the density. In this case the phase velocity is given as in eq. (7)

$$c \quad \sqrt{\frac{B}{\rho_0}} \quad \sqrt{\frac{1}{k\rho_0}} \tag{7}$$

and k is the compressibility as taken from

$$k \quad \frac{1}{B} \tag{8}$$

Ultrasonic velocities (primarily) and energy attenuation (secondarily) are measured since they get unique values for different types of propagating medium. It should be noted that the ultrasonic signal has different velocities for different materials (or phases). Moreover, in an inhomogeneous medium, the signal propagates with no constant velocity; the signal takes the velocity of the material in which it travels at each instant. The libraries of ultrasonic velocities are widely available [7]. Matching measured and *a priori* values yields the identity of a scanned material. Acoustic interrogation signals are non-invasive and non-destructive. Furthermore, they are rapid and low cost. Acoustic scanning has the best performance when searching for solid materials in a liquid medium.

Muon scattering

Muons are highly energetic particles produced by the interaction of cosmic rays with the atoms in the upper layers of atmosphere

$$\pi \qquad \mu \qquad \nu \tag{9}$$

$$\pi \qquad \mu \qquad \bar{\nu} \tag{10}$$

Muons, after traveling long distances, decay into an electron, neutrino, and antineutrino. The decay of muons is characterized by a constant decay rate λ, and the decay time distribution is expressed by

$$D(t) \quad \lambda \exp(\ \lambda t) \tag{11}$$

where the lifetime of a muon is defined as

$$\tau \quad \frac{1}{\lambda} \tag{12}$$

Their large rest mass (105.7 MeV/cm^2) means that no terrestrial nuclear event is capable of generating muons. Approximately 10^4 muons per square meter reach the surface of the earth in a given minute. The average kinetic energy at sea level is about 4 GeV. This corresponds to a continuous slowing down approximation (CSDA), mean penetration ranging from several meters in common construction and shielding materials (concrete, steel, lead, *e. g.*) to kilometers in case of gases such as those used in detectors. It is, therefore, practically impossible to shield a cargo against muon interrogation. Additionally, their high energy relative to their rest mass means that muon scattering can be treated as an inelastic collision with a reasonable degree of accuracy. Therefore, the scattering angle is primarily a function of the mass of the target nucleus. Given a statistically large number of scattering events, the mass of the nucleus can be measured using the muon scattering angle.

The problems of low detector efficiency are compounded by the need to detect both the incident and scattered muon in order for the trajectory data to be calculated. If a detector of 10% efficiency (an order of magnitude better than the current technology) were constructed, only 1% (0.1^2) of muon interactions could be detected. For example, in a one meter lead cube, there will be an average of 805 muon scattering events per second, out of which about 8 will be measured. In a smaller target, for example a 10 cm cube, 0.008 detection events can be expected per second, using this hypothetical 10% efficient detector. Using a one-hour scanning time, 29 trajectories could be measured, which is approximately the minimum needed for the statistical analysis.

Their scattering yields a spectrum which uniquely characterizes the penetrating material. On the other side, muons' high energy prevents them from being detected easily. The use of large detectors and long scanning time is an unavoidable part of this new detection process.

NRF scanning

NRF scanning uses photons of high energies to induce the resonance states within the target nucleus and the subsequent decay of these levels by re-emission of the nearly equivalent photon. Every isotope ($Z > 2$) has a characteristic "nuclear signature" as a result of the unique arrangement of protons and neutrons in its nucleus. This technique uses a bremsstrahlung gamma beam (commonly an electron linear accelerator, fired at a tungsten target) to check for resonance states within the target nucleus (fig. 1). When the nucleus is excited by a polychromatic gamma ray, it re-emits gammas at these characteristic energies. The resonance fluorescence cross-section, without considering Doppler broadening, is described with a Breit-Wigner formula

$$\sigma(E) \quad \pi \ \frac{\lambda}{2\pi}^{\,2} \frac{2J_1 \quad 1}{2J_0 \quad 1} \frac{\Gamma_0(\Gamma/2)}{(E \quad E_r)^2 \quad (\Gamma/2)^2} \tag{13}$$

where λ and E are the wavelength and energy of the incident photon, E_r is the resonance energy of a nucleus, J_0 and J_1 are the nuclear spins of the ground and excited states, Γ is the total decay width of the excited state, and Γ_0 is the partial width of the electromagnetic de-excitation. NRF provides an exacting precision for material detection. This detection is under development and is not a part of the current cargo scanning systems.

Figure 1. NRF with bremsstrahlung radiation

Motivation for selection and synergy of signals

The signals mentioned in the previous section determine the channels of information for the cargo inspection. Each signal factors into the final decision according to its characteristics and properties. Individually all four signals can also stand alone for cargo interrogation and the detection of hazardous materials, as each of them has unique properties that enable the detection.

X-rays penetrate the cargo and by constructing the CT image the presence of high Z material is revealed. Moreover, the exact position of the materials is given by the coordinates of the voxels. This establishes a region of interest for further interrogation.

Ultrasonic-acoustic scanning propagates through the material, and if it meets more than one different type of material, it yields an unknown velocity. This alerts us for the presence of something unknown to us in the otherwise homogeneous cargos. Moreover, in case we know the cargo interior is homogeneous, the ultrasonic shifts caused by materials can be computed. This leads to the identification of materials too.

Muon scattering by tracking cosmic muons entering and exiting the cargo can detect the presence of SNM. This is possible because the spectrum obtained shows the detected angles.

Nuclear resonance fluorescence scanning yields a spectrum of background and possible NRF peaks. All materials have their own signature which is based on the absorption and subsequent re-emission of gamma rays. The detection of the characteristic peaks leads to the material identification.

However, each signal by itself provides a standalone path for interrogation and detection. The integration of all of them at the same time seems to offer a wide field of view for fast and effective detection. So challenging all of them at the same time means that a well structured synergy is needed. Moreover, the cooperation of the four signals should exploit their unique properties and enhance the detection capability.

To that direction, the proposed methodology integrates the above signals into a layered algorithm. The basic idea is that each layer has a goal to finish the detection procedure. If this is not possible, then it should pass to the next level while maintaining efficiency. The flow of the algorithm goes from the simpler method to the more complex ones. In other words, the detection is performed by each signal separately, but at the same time, the cooperation is utilized.

The structure of the synergy, applied to the algorithm, exploits the strong aspects of each of the four signals. Radiography/CT marks the suspected areas and gives this information to the next level. Acoustic scanning takes place at slices indicated by radiography/CT and attempts to identify the interior of as many voxels as possible. Then the remainders undergo muon and NRF inspection since these are the most time consuming methods.

Fuzzy logic was selected since it provides a powerful frame for decision making. Its principle advantage is that it tries to mimic the way humans think and decide. Fuzzy logic is not based on crisp sets and helps us to model uncertainty and doubt. It was selected since the detection can not be strictly binary. We did not want just a strict threshold. Since we use more than one signal more uncertainty gets into the decision making procedure. In case signals yield different results, fuzzy logic shows that discrepancy qualitatively. At the end, it provides us with the probabilities of SNM presence.

Thus the algorithm provides a well structured hierarchy and cooperation of the different types of information.

Detection algorithm

The proposed detection algorithm consists of several autonomous steps. The separation into *detection layers* is attainable due to the ability to process multiple types of signals. Such layering advances a quick detection and consumes a minimum amount of resources. The algorithm is shown in fig. 2. Initially,

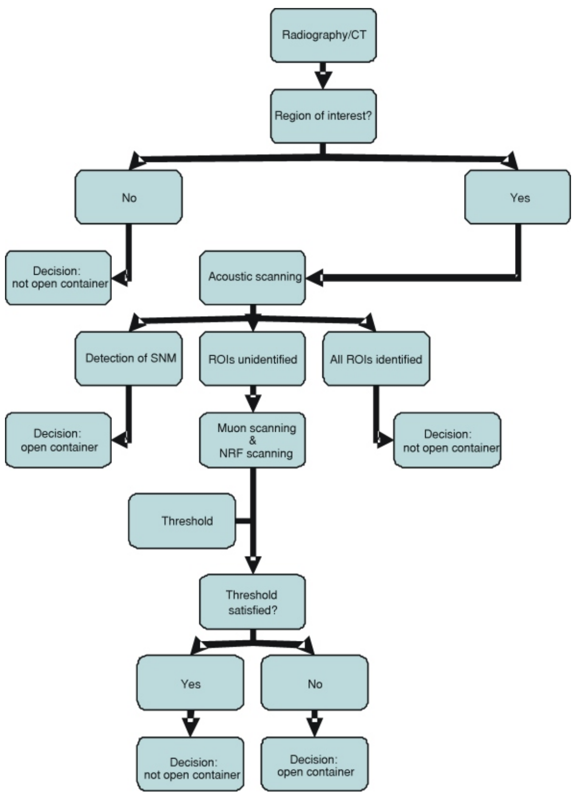

Figure 2. Flowchart of the multisignal detection algorithm

we assume that the radiographic images of the cargo are obtained, or the CT scan of the container is constructed. Additionally, CT marks all voxels that possess high *Z* materials. In case such voxels do not exist, the inspection is ended. If the opposite occurs, the inspection is led to the next level. We assume that in the next step, the acoustic scanning is performed targeting the ROIs to obtain the ultrasonic velocities. The interrogation of this type is applied in two directions (length axis, width axis). The obtained velocities are compared to the known values stored in acoustic-databases. The matched values allocate the automated identification of the materials. If the unidentified ROIs remain, the algorithm moves on to further interrogation. A predetermined threshold value for decision making is necessary. This value contributes significantly to the final decision. The recommended values are inside the interval 80-95%. This threshold represents an analytic form of our confidence for identification of hazardous materials. If the final decision is not reached, the muon scattering data is assumed to be available. The data is proportional to the characteristic muon scattering angle. Any additional signals will come from the NRF interrogation. The intelligent decision making is integrated within the synergy of the presented four signals. If the final output value satisfies the predetermined threshold then a manual search is not needed. In any other case, the opening of the container is mandatory.

Intelligent decision-making module

The intelligent decision making module is the brain of the algorithm. It is applied in the last part of the algorithm to reach a final decision. Initially, the preliminary part of the intelligence module uses the data from the radiography and acoustic scanning steps. ROIs that were marked by radiography are matched with SOIs (slices of interest) from the acoustic scanning to construct the reduced CT image of the container. This is possible since the acoustic scanning was performed in two dimensions. Using the coordinates of voxels from radiography and identified materials from SOIs, we are able to get a new three-dimensional image of the container with the reduced number of ROIs. The SOIs indicated include a known material having coordinates given as a set of two numbers: (x, z) for scanning the length and (y, z) for scanning the width. The length, width and height are denoted as x, y, and z, respectively. The fusion of data from the two scans is performed as following: lists with the identified SOIs are compared and those that have the same z are placed on a new list with the fused data:

– check list of unidentified SOIs from the length scanning with the coordinates (x, z),
– check list of unidentified SOIs from the width scanning with the coordinates (y, z), and
– all duplets of the two lists that have the same z are fused and the triplets of (x, y, z) are created.

As a result, the new list contains the triplets (x, y, z) that denote the coordinates of the unidentified voxel from the acoustic scanning. The new list is superimposed with the coordinates obtained from the CT image or radiographies. The common sets are put aside as ROIs that need further interrogation.

The core of the intelligent module uses fuzzy logic to analyze muon and NRF data. Initially the spectrum is preprocessed. Its mean and its standard deviation are computed. Then all the locations, i, of the spectrum are marked as the candidate peaks, satisfying

$$counts(i) \quad mean(spectrum) \quad std(spectrum) \tag{14}$$

Fuzzy logic is used to determine the probability of the detection. For example, the characteristic NRF peaks of materials of interest are captured by triangular fuzzy sets. These sets have a very narrow membership function which gets the value of one at the central locations of the NRF peak. The output sets use membership functions of the form

$$\mu(y) \quad \frac{1}{1 \quad \left(\frac{y}{5}\right)^{3}} \tag{15}$$

The output is always a number in the range [0, 1] which denotes the probability. The fuzzy rules are used to assign peaks to the materials. Fuzzy rules have the following form:

– R1: If the peak at the position $p1$ is detected with the membership $a1$, then aluminum is detected with confidence $c1$,
– R2: If the peak at the position $p2$ is detected with the membership $a2$, then aluminum is detected with confidence $c2$, and
– R3: If the peak pn is detected with the membership an, then lead is detected with confidence $c3$.

If more than one rule is used then the AND operator is employed to make inferences. The implication operator of mamdani min is used for relating the input and the output sets

$$\phi_{c}[\mu_{A}(x), \mu_{B}(y)] \quad \mu_{A}(x) \quad \mu_{B}(y) \tag{16}$$

where $\mu_A(x)$ denotes the membership function of the input set A and $\mu B(x)$ the output set B.

The composition of all rules for the detected peaks assigns probabilities to materials of interest and indicates the interior of the voxels. This occurs by the superposition of the fuzzy sets and measured spectra. A similar approach is used for muon scattering data spectra with the exception that the bell shaped functions are used to represent angles

$$\mu(x) \quad \frac{1}{1 \quad 0.1(x \quad 2)^{2}} \tag{17}$$

In this case the fuzzy sets are placed to areas where these characteristics angles of hazardous materials appear. Again, the superposition of the fuzzy sets and the obtained spectra yields matching probabilities for identified nuclear signatures.

At the end the decision is made by synthesizing the two probabilities. This happens by just taking their mean value, as

$$Mean(voxel) \quad \frac{\Pr(NRF) \quad \Pr(Muons)}{2} \tag{18}$$

Then the computed mean value is compared with the threshold to decide on manual search or not

$$Mean(voxel) \quad threshold \tag{19}$$

$$Mean(voxel) \quad threshold \tag{20}$$

If eq. (19) is true then the algorithm flags the container as suspicious and decides on its manual opening. In case eq. (20) is true, then the container is classified as not suspicious.

MULTISIGNAL COMPUTATIONAL SCANNING: A CASE STUDY

This section describes the four-signal detection algorithm in detecting the SNM in the cargo interior. The test case is a highly simplified cargo structure. The main goal is to test the algorithm's accuracy and speed.

Cargo geometry

The multisignal detection algorithm was applied to a typical ocean-shipped cargo container. The dimensions of the container are: 5.9 2.3 2.4 m (length × width × height). The cargo is voxelized; each voxel has a rectangular shape with the dimensions: 10 10 cm.

We will assume that the SNM is hidden inside the cargo containing the barrels filled with liquids. We assume the liquid to be water. Also, we select that materials to be found in the cargo are: lead, iron, carbon, depleted uranium, and aluminum. Fuzzy sets are used for these elements.

The acoustic scanning assumes a directed ultrasonic interrogation. The velocity values are obtained for two-dimensional interrogation: along the cargo's length and along the cargo's width. The interrogation along the third dimension is not feasible in reality.

The NRF and muon scattering spectra are simulated using the Geant4 [8]. All NRF spectra except for U-238 are generated using the Geant4. The U-238 NRF spectrum is synthesized in Matlab according to Nudat2 library [9]. All these spectra were used as the obtained spectra of the cargo inspection and also provided us the necessary pad to create the fuzzy membership functions. The confidence level is set to the interval 80-90%.

The procedure was done in Matlab. All individual steps of the algorithm were implemented using Matlab. The cargo container is represented by a three-dimensional matrix. Each matrix entry can be filled with one out of the six materials.

Computational approach

Initially, the cargo was modeled as a three-dimensional (3-D) matrix. In order to represent the real cargo, a scale of 1 to 10 cm was used. Each entry of the matrix represented a voxel. The CT image of the cargo was obtained by logically searching through the matrix, and unknown entries were flagged as ROIs. To simulate and test the algorithm, the *Z* number was preprogrammed for each voxel, but the program runner was blind to the location of the material. A 3-D plot of the cargo is obtained, and voxels were plotted with different grayscale color to denote differences in the atomic number. Moreover, the coordinates of the ROIs are stored in a matrix and passed to the next level.

For the acoustic scanning, a library of the known acoustic velocities was developed. In addition, the library was enhanced with all the shifts that the materials caused relative to the ultrasonic velocity of water. This was done on a voxel scale; *i. e*. the shifts were computed for a material that occupies one voxel, two voxels, and so on. The ultrasonic velocities of each SOI were computed by adding the velocity of each voxel and then dividing by the total number of the traversed voxels. The comparison of the scanned velocity and the shift that caused to that of water were compared with the entries of the libraries. Velocities "matched" when their acoustic difference was smaller than 0.25. This indicated that a material was correctly identified. The acoustic data were obtained from scanning both the length and width. The unidentified ROIs were stored in a matrix and inherited to the next interrogation step.

The muon scattering used the matrix of the unknown voxels from the previous stage. For the materials of interest, spectra were simulated using Geant4 and stored in files. Fuzzy sets developed by the fuzzy toolbox of Matlab were used on the invoked spectrum to detect the peaks.

The same approach as for muons was used for the NRF computational scheme. The NRF spectrum was simulated in Geant4, and it was passed into Matlab for fuzzy logic interpretation.

Scanning procedure and results based on the four-signal algorithm

The first level of detection assumes the X-ray inspection of the cargo. Figure 3 shows the CT image to

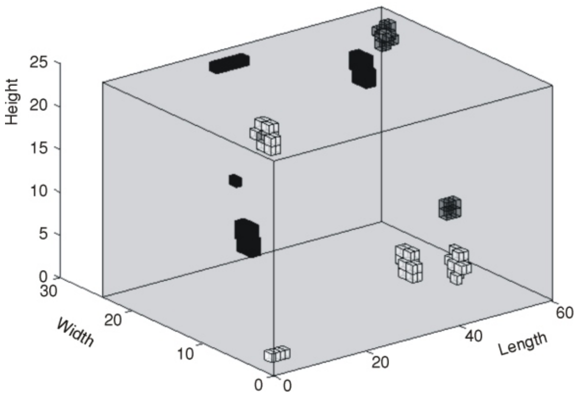

Figure 3. Cargo CT image with the identified ROIs made in Matlab

be obtained; the ROIs are identified. The simulation was done in Matlab, and all materials but water were marked as suspicious. Different intensity of color implies different *Z* number. The presence of ROIs indicates that the further inspection is required. In this test case a total of 103 voxels are flagged as suspicious. As a result, the algorithm "calls" for the next detection system layer of the algorithm.

The next detection system is based on the acoustic scanning. The efficiency of detection using the ultrasonic velocity is improved if the interrogation is performed in two dimensions: along the cargo's length and width. Both scanning orientations are indicated in fig. 3. The velocities that do not match that of water imply the existence of other materials along the slices acoustically examined; such slices are marked as slices of interest. The ultrasonic measurements of SOIs are compared with those stored in our database. The matched values identify the materials in each of the SOIs. The combination of SOIs (fig. 4) allow for more accurate identification of materials resulting in a reduction of initially found ROIs. As indicated in tab. 1 this interrogation helped enhance the detection efficiency of iron, lead, aluminum, and carbon. However, some of the regions are not identified. The coordinates of the unidentified SOIs are given in tab. 2.

Table 1. Materials detected from acoustic scanning

Acoustic scanning	
Length	Width
Materials detected	
Iron (Fe)	Iron (Fe)
Lead (Pb)	Lead (Pb)
Aluminum (Al)	Aluminum (Al)
Carbon (C)	Carbon (C)

The materials detected so far are not classified as hazardous. Up to this point, no positive decision for further manual search is taken. The unidentified interior of some voxels "calls" the algorithm to move to the final step. Slices that might not have been identified by the acoustic length scan are possible to have been identified by the acoustic width scan and *vice versa*. The common unidentified voxels are obtained from the common *z* coordinate. All values of *z* that appear in both methods qualify for the next stage. In this test case, the fusing process produces a set of four voxels. Figure 4 shows the cargo interior with fewer ROIs to be identified with the remaining scanning methods.

The number of suspicious areas has dramatically reduced from 103 to 4. The identification of lead enhances a suspicion of the presence of SNM in the liquid since lead is expected to be a shielding material for depleted uranium. Muon and NRF are thus computationally applied as a dual scanning protocol to the set of voxels indicated by the acoustic scanning.

Table 2. Unidentified SOIs after acoustic scanning

Slices of interest						
Coordinates						
Scanning length		Scanning width		Common (fused)		
x	*z*	*y*	*z*	*x*	*y*	*z*
		4	4			
10	10	4	5	10	10	10
24	17	5	4	24	17	17
50	20	5	5	50	20	20
58	22	10	10	58	22	22
		17	17			
		20	20			
		22	22			

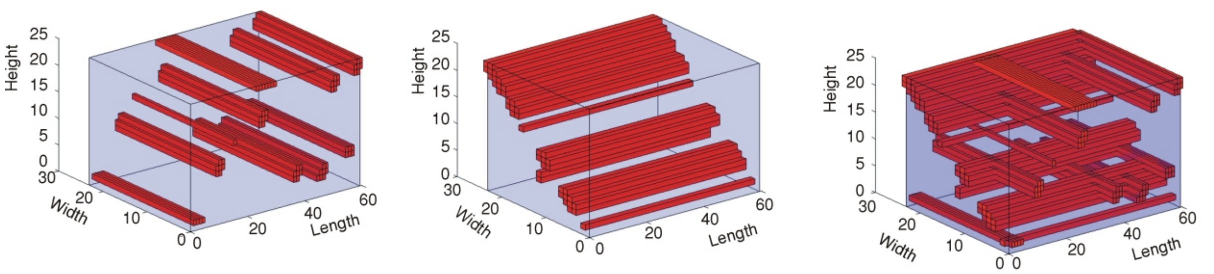

Figure 4. SOIs (bars) obtained after ultrasonic interrogation across length (left), across width, and combination of them (right)

The NRF scanning performed in the remaining four voxels yielded matching probabilities for the materials of interest. Probabilities were assigned by fuzzy sets. The same approach is applied to muon detection. Table 3 presents the statistics obtained from the synergy of these methods.

The NRF spectrum obtained for the first voxel is presented in fig. 5. The uranium is detected in two voxels with high probability. Muon scanning also detects the U-238 (fig. 6) with the probability over the threshold of 90%. For the same cases NRF yields 80% confidence level. This value is not as high as 90% but is considered to be significant. Taking into consideration both values (muon, NRF) we reach a decision: the container should be singled out for a manual search.

Table 3. Matching statistics for NRF and muon inspection

Material	Matching statistics							
	Voxel 1 (10, 10, 10)		Voxel 2 (24, 17, 17)		Voxel 3 (50, 20, 20)		Voxel 4 (58, 22, 22)	
	NRF	Muons	NRF	Muons	NRF	Muons	NRF	Muons
Pb	0	0.1111	0	0	0	0.1111	0	0
Al	0	0	0	0	0	0	0.95	1
C	0	0	0	0	0	0	0	0
Fe	0	0	0.85	1	0	0	0	0
U-238	0.8	1	0	0	0.8	1	0.8	1
DECISION: Container needs further manual search due to detection of uranium								

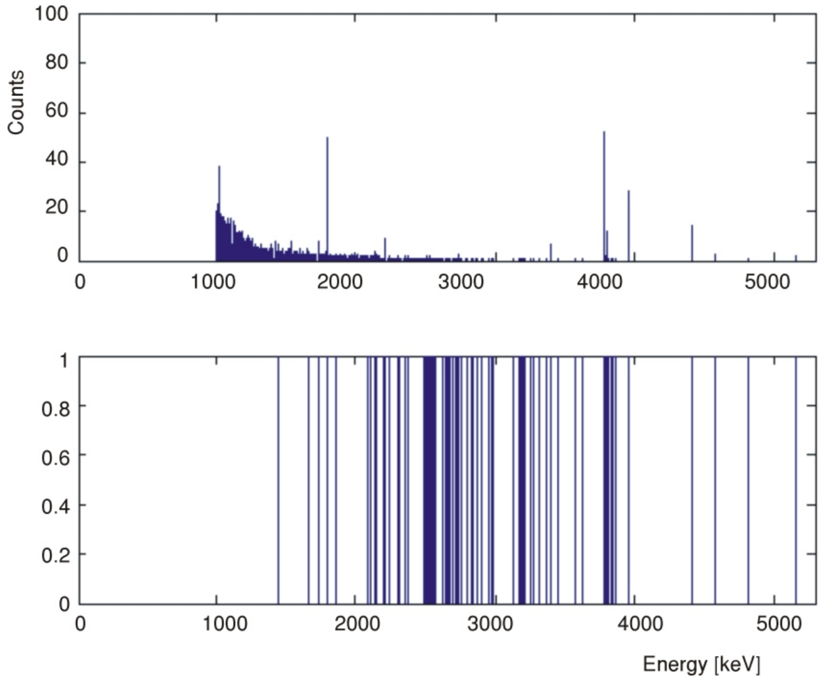

Figure 5. NRF spectrum for voxel 1 (U-238) and detected peaks

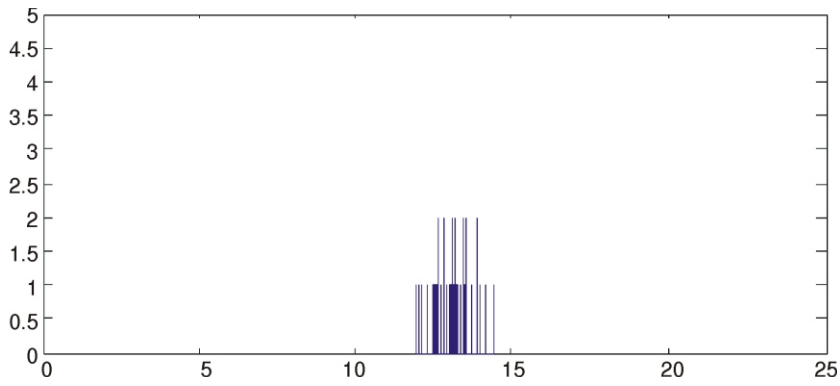

Figure 6. Muon scattering spectrum obtained for voxel 4 (aluminum)

The algorithm performs efficiently and quickly. In order to get a good notion of the scanned time we iterated the scanning procedure six times using the same interior. The results for the decision time are presented in tab. 4. Each pass of the algorithm occurred in time less than 8 s. The time needed to inspect spectra for a single voxel is about 1.1 s. This means that the time of decision was reduced because of the first part of the algorithm: CT and acoustic. The total absence of this part would lead to NRF or muon scanning of every single voxel which would require long decision time.

Table 4. Decision making time for 10 scanning trials of same container

Scanning time			
Iteration	Time [s]	Iteration	Time [s]
1	7.7495	6	7.7656
2	7.7831	7	7.7616
3	7.7527	8	7.7245
4	7.7681	9	7.7371
5	7.7416	10	7.7354

CONCLUSIONS

The multisignal algorithm is based on a fusion of four different detection techniques. The capability of processing four signals (radiography/CT, acoustic interrogation, muon detection, and NRF spectra) was tested for a cargo filled with water and various heavy metals. A precise decision was made in a short period of time (7.8 s). The four detection techniques used in series proved to be efficient in identifying and reducing the regions of interests for each succeeding step of the inspection. The intelligent decision making module contributed in that direction by merging data from the radiography and acoustic scanning and then fed the filtered data to the other two methods. The time intensive muon and NRF interrogation would then be sped up linearly for each voxel that was deemed trivial in the previous layers of the algorithm. If it weren't for that preliminary step then we would have checked 206 spectra (two for each ROI). Future work will embed Geant4 radiography [10] into the proposed algorithm. Also, fuzzy logic tools will be used in acoustic measurements to improve the detection time. Fuzzy logic can help reduce the volume of the acoustic library and this will result in shorter time of searching for matches. Furthermore, the Geant4 simulated NRF and muon spectra will be obtained and a database will be developed. The porting of the algorithm to a faster language (such as C++) will improve its speed.

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REFERENCES

[1] ***, Hitachi, Cargo Container X-Ray Inspection Systems, *Hitachi Review, 53* (2004), 2, pp. 97-102

[2] Hall, J. M., Asztalos, S., Biltoft, P., Church, J., Descalle, M.-A., Luu, T., Manatt, D., Mauger, G., Norman, E., Petersen, D., Pruet, J., Prussin, S., Slaughter, D., The Nuclear Car Wash, Neutron Interrogation of Cargo Containers to Detect Hidden SNM, *Nuclear Instruments and Methods in Physics Research, 261* (2007), 1-2, pp. 337-340

[3] Bertozzi, W., Korbly, S. E., Ledoux, R. J., Park, W., Nuclear Resonance Fluorescence and Effective *Z* Determination Applied to Detection and Imaging of Special Nuclear Material, Explosives, Toxic Substances and Contraband, *Nuclear Instruments and Methods in Physics Research, 261* (2007), 1-2, pp. 331-336

[4] Diaz, A. A., Burghard, J. B., Skorpik, R. J., Shepard, L. C., Samuel, J. T., Pappas, A. R., Non-Invasive Ultrasonic Examination Technology in Support of Counter-Terrorism and Drug Interdiction Activities – the Acoustic Inspection Device (AID), *Proceedings of SPIE*, The International Society for Optical Engineering: Non-Destructive Detection and Measurement for Homeland Security, San Diego, Cal., USA, March 4-5, 2003, pp. 34-45 (Paper 61908)

[5] Priedhorsky, C. W., Borozdin, N. K., Hogan, E. G., Morris, C., Saunders, A., Schultz, J. L., Teasdale, E. M., Detection of High-*Z* Objects Using Multiple Scattering of Cosmic Ray Muons, *Review of Scientific Instruments, 74* (2003), 10, pp. 4294-4297

[6] Tsoukalas, H. L., Uhrig, E. R., Fuzzy and Neural Approaches in Engineering, John Wiley and Sons – Interscience, New York, USA, 1997

[7] Diaz, A. A., Burghard, J. B., Valencia, D. J., Samuel, J. T., Ultrasonic Database Development for the Acoustic Inspection Device, the Velocity-Attenuation Measurement Sustem (VAMS), *Proceedings of SPIE*, The International Society for Optical Engineering: Non-Destructive Detection and Measurement for Homeland Security II, San Diego, Cal., USA, March 16-17, 2004, pp. 26-35 (Paper 63677)

[8] ***, Geant4 Home Website, Geant4.web.cern.ch/geant4

[9] ***, Interactive Nuclear Structure and Decay Databases, www.nndc.bnl.gov/nudat2

[10] Perry, J., Xiao, S., Jevremovic, T., iMass: Evolved NRF Simulations for More Accurate Detection of Nuclear Threats, *Proceedings,* 17th International Conference on Nuclear Engineering, Brussels, July 12-16, 2009

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ВИШЕСИГНАЛНА ДЕТЕКЦИЈА ПОТЕНЦИЈАЛНО ОПАСНИХ МАТЕРИЈАЛА

Развијање метода за детекцију потенцијално опасних материјала један је од најпримарнијих интереса у САД, нарочито када је у питању прегледање бродских терета на њеним границама. Специјални нуклеарни материјали (СНМ) уобичајено се детектују на основу метода које користе неутронско или гама зрачење. Од недавно се разматра коришћење методе која се заснива на примени нуклеарне резонантне флуоресенције (НРФ). У овом раду, ми смо описали нови прототип система за детекцију опасних материјала у бродским контејнерима, који се заснива на анализи четири сигнала (радиографија или скенер, акустични сигнал, мионско расејање и НРФ). Развили смо теоретски алгоритам који обавља интелигену анализу система сигнала користећи следећи сценарио: најпре претпостављамо да је могуће добити радиографски или скенер снимак контејнера који би омогућио прву идентификацију региона од интереса (РОИ); акустично тестирање би се користило синергетски са радиографијом или скенером и дало би информације о ултразвучним брзинама у контејнеру. Суперпозиција радиографских/скенер података и акустичних брзина редуковала би величину РОИ. У следећем кораку алгоритам би одлучио да ли је неопходно наставити детекцију примењујући преостале две методе. У случају да је одлука да се настави тестирање контејнера, мионско расејање би произвело спектар чијом анализом би могло да се одреди присуство материјала великог атомског броја. И на крају, НРФ сигнал би дао тачну идентификацију који су материјали присутни у контејнеру. Овај нови предложени алгоритам основан на фузији четири различита сигнала тестиран је за детекцију СНМ у контејнеру стандардних димензија.

Кључне речи: детекција нуклеарних материјала, скенирање контејнера, вишесигнална детекција, фази логика, интелигентна одлука