RADIOSCOPIC DISCRIMINATION OF MATERIALS IN 1÷10MEV RANGE FOR CUSTOMS APPLICATIONS

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Abstract

The paper demonstrates that useful for the customs purposes discrimination of four groups of materials according to atomic number is obtainable by means of pulse-by-pulse irradiation of cargo by bremsstrahlung beam with 8 MeV and 4 MeV dual boundary energies. An industrial linear electron accelerator with dual energy is used as bremsstrahlung source. The scintillating crystals coupled with silicon photodiodes are used as detecting elements of the detector line. It is shown that the integral dose accumulated by a detector in the customs scanning mode for the high and low energy profiles is not sufficient to provide the necessary signal-to-noise ratio for reliable material discrimination. Despite the low sensitivity of method in the given energy range a denoised distribution of atomic number is restored by means of application of image segmentation technique to the dual image. High quality images visualizing integral absorption and effective atomic number are produced in IHS colorization scheme. All experiments were fulfilled on a full-scale prototype of inspection system developed in the Efremov Research Institute.

1 INTRODUCTION

In our previous works [1-2] it was shown that radioscopic discrimination of materials according to atomic number (*Z*) in 1÷10 MeV range is achievable. Effective atomic number of material can be evaluated from a pair of experimentally measured radioscopic transparencies at high and low boundary energy of bremsstrahlung. The discrimination effect between materials is due to the effect of electron-positron pair production and is quite small for materials with similar atomic numbers. For example, for water and polyethylene with $\Delta Z \approx 2$ it totals only about 1%, but between polyethylene and iron $\Delta Z \approx 20$ it is already around 10%. Discrimination slightly increases with thickness growth as far as x-ray spectrum undergoes hardening, but rapid growth of noise conditioned by the exponential fall of bremsstrahlung intensity degrades discrimination effectiveness. For reliable evaluation of atomic number an accurate measurement of integral absorptions with precision at least three significant digits is needed.

2 EXPERIMENTS

Verification of practical realizability of material discrimination was made in a series of experiments fulfilled on a full-scale prototype of customs inspection system developed in the Efremov Research Institute.

The basic technological equipment of the system included industrial linear electron accelerator with energy 8/4 MeV and repetition rate up to 150 Hz, collimating system forming vertical fan-shaped bremsstrahlung beam, detector line with $CdWO_4$ crystals coupled with PIN diodes as sensitive elements with 3.5 mm pitch, transportation system of tested objects.

During experiments the accelerator operated at so called interlaced mode, when each even pulse generated high-energy bremsstrahlung and each odd - low. Such scanning scheme made it possible to form dual radioscopic images of tested samples and container.

As a tested object for transparency evaluation, a steel step-wedge with 2.5, 5.0, 7.5, 10.0 and 15.0 cm steps was taken. The primary bremsstrahlung was filtered by 0.4 cm lead plate. In experiment, the boundary energies of high and low x-ray beams evaluated by the absorption method equaled 7.5 and 4.6 MeV correspondingly. The radiation dose absorbed by detectors per single scan totaled 330 μGy for high energy and 30 μGy for low one. Both transparencies were obtained by averaging pixels belonged to each barrier and given in table.

Discrimination error between polyethylene and iron as characteristic materials of organic and inorganic groups was numerically estimated in accordance to the Bayesian formula [3] at different attenuation rates.

Experiments showed that 40-60gm/cm^2 mass thickness range is optimal for material recognition and characterized by the minimal discrimination error. In the simplest case, when organic-inorganic separation is needed only, the satisfactory solution is achievable even without any processing of dual data.

In the more common case, for example, for four groups of materials representing interest for customs control, the effectiveness of discrimination is deteriorated and materials recognition becomes unreliable (fig. 1). The customs scanning scheme does not provide sufficient dose absorbed by single detector and, therefore, necessary signal-to-noise ratio on dual image.

3 PROCESSING

The problem of high dispersion of the dual data, appeared as colored pepper-and-salt noise at visualization of material recognition results (fig. 1), can be solved if data processing methods, based on human eye perception features, are used for the noise suppression.

We propose a data treatment scheme, in which a processed dual image is divided into the fixed number of meaningful regions associated with different components of container cargo. The method consists of a few steps.

The first step performs a rough segmentation of image according to the modified leader algorithm of data clustering. The second step reduces the oversegmentation by selectively merging neighboring regions with small area. The third one labels the survived clusters and associates them with cargo substances.

The choice of leader algorithm [4] for segmentation of radioscopic images of containers is stipulated by the following conditions. Firstly, the number of partitionings is not known a priory as far as inspected containers are usually filled with arbitrary cargo. Secondly, the algorithm must be based on one-pass (non-iterative) data treatment scheme only due to the requirement of high throughput of the customs system.

Measurements of transparencies are significantly affected by noise, which corrupts the image partitioning and stipulates overlapping of clusters with similar transparencies. Employment of statistical classification methods such as classical leader algorithm does not allow separating clusters of different materials with equal mass thickness and, therefore, perform reliable discrimination.

Nevertheless, there is a possibility to separate the merging clusters, if their geometrical disposition is taken into account. This approach requires a modification to the classical leader algorithm in order to take into account the spatial aspect of image data. In the new scheme a pixel is included to a certain cluster only in case of its geometrical adjacency on the image to any of members constituting the cluster. Thus, the cluster with certain label consists of pixels not only having similar transparencies, but spatially adjacent to each other. This allows more accurate evaluation of cluster centers and, consequently, atomic numbers of objects, as far as discrimination in such scheme is realized not pixel-by-pixel, but on segment-by-segment basis.

In order to suppress residuary noise due to presence of small sized clusters and to preserve fine structure of the output image, a proper merging of irrelevant clusters has to be applied. The scheme assumes an iterative merging of neighboring regions with similar transparencies. The merging criterion is taken from the hypothesis assuming that population means are equal. For small area clusters a Student's T-test is most suited [5]. In such case of digital enlargement of segments by selective merging, the spatial resolution remains almost intact, as the spatial shape of the spots is effectively adapted to the variation of intensity on the image.

Fusion of segmented distribution of atomic number and integral absorption was carried out in Intensity-Hue-Saturation (*IHS*) color space [6], which most closely corresponds to the human eye perception physiology. In the *IHS* scheme adapted to material recognition task, intensity denotes transparency, hue represents atomic number and saturation characterizes the degree of material discrimination. For visualization of four material groups representing interest at the customs control the following four color hues are chosen: red (organics), green (overlapping organics and inorganics), blue (inorganics) and lilac (heavy metals).

The production of the fused output image in such scheme includes the following steps:

1. Transformation of atomic number into color hue in *IHS* color space;
2. Determination of color intensity from high energy image restored by means of point spread function;
3. Backward projection from *IHS* to *RGB* color space for visualization.

Result of image fusion is demonstrated on fig. 2.

4 CONCLUSION

The routine measurements of dual integral absorption rate by the scintillator-photodiode pair in 1÷10MeV range do not allow achieving complete discrimination of materials in container.

The image segmentation technique based on the modified leader clustering algorithm allows to suppress noise in a certain extent and perform discrimination of four basic material groups irrespective to mass thickness.

The dual energy radioscopic discrimination of materials according to atomic number was demonstrated on the customs inspection system with 8/4MeV dual boundary energies.

TABLE Experimentally measured transparencies *(T)*, signal-to-noise ratio *(SNR)* for high (E_1) and low (E_2) energy images, ratio of logarithmic transparencies (R), its error (δ_R), discrimination effect ($D_{CH2,Fe}$) and discrimination error (P_{err}) for organic and inorganic group of materials as function of mass thickness. Data are given for a steel step-wedge.

	Mass thickness t, gm/cm^2					
	0	20	40	60	80	120
$T(E_1)$	1.0	0.437	0.204	0.0989	0.0491	0.0127
SNR_1	221	136	98	64	42	23
$T(E_2)$	1.0	0.373	0.153	0.0658	0.0295	0.0065
SNR_2	76	43	27	17	9	4
R	–	0.843	0.847	0.851	0.856	0.864
δ_R , %	–	2.4	2.1	2.3	3.3	5.2
$D_{CH2,Fe}$, %	–	5.9	7.0	7.8	8.4	9.4
P_{err} , %	–	9.9	3.4	4.5	10.8	19.7

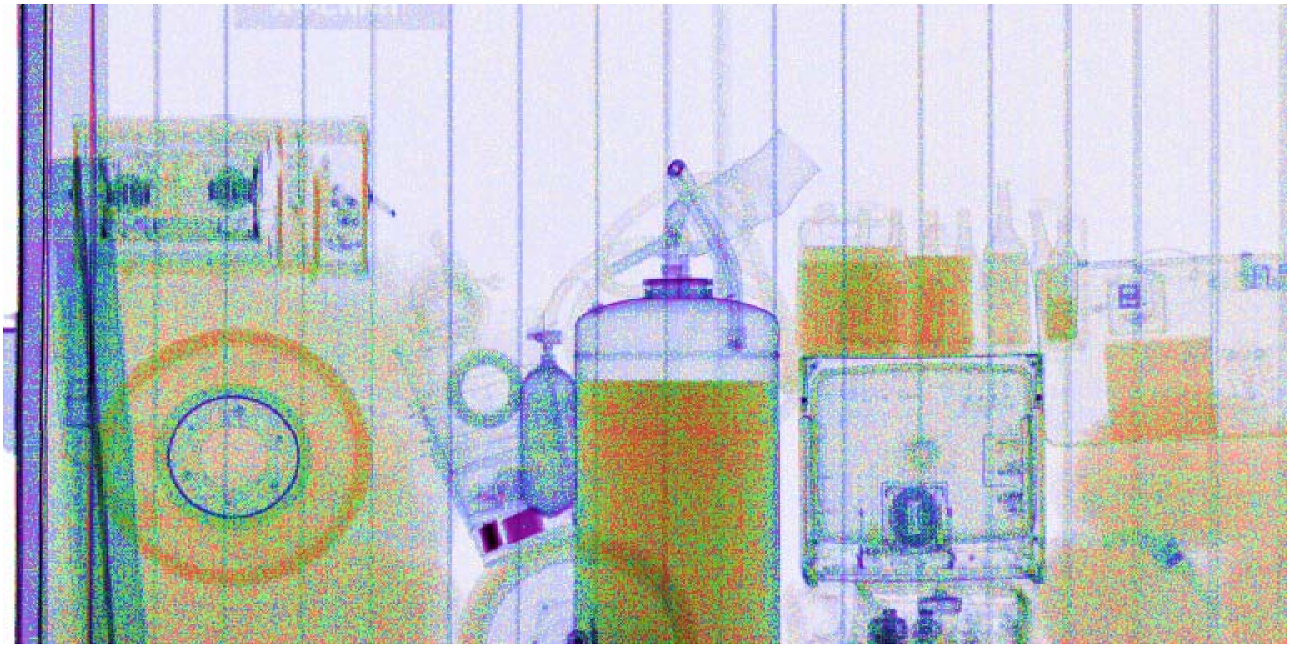

FIG. 1. (Color) Colorization of shipping container image is fulfilled on pixel-by-pixel basis without any processing.

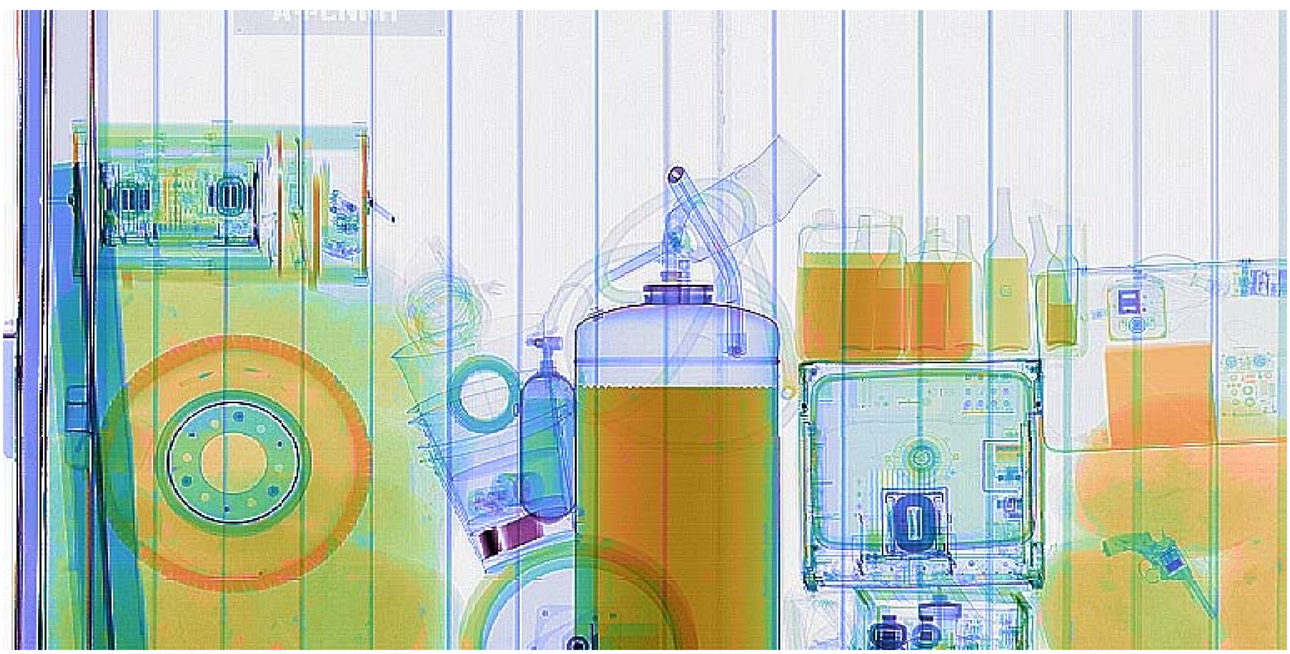

FIG. 2. (Color) Colorization of shipping container image is fulfilled after the segmentation procedure.

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