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Experimental Research of High-Energy Capabilities of Material Recognition by Dual-Energy Method for the Low-Dose Radiation

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Abstract. The algorithm to produce primary radiographs, its transformation by dual energy method and recognition of the object materials were enhanced based on the analysis of experimental results. The experiments were carried out at the inspection complex with high X-ray source − betatron MIB 4/9 in Tomsk Polytechnic University. For the reduced X-ray dose rate, the possibility of recognition of the object materials with thickness from 20 to 120 g/cm^2 was proved under the condition that as the dose rate is reduced by the defined number of times, the segment of the image fragment with the reliably identified material will increase by the same number of times.

1. Introduction

Recognition of materials of the object of inspection control and its fragments remains one of the most important problems to be solved by the customs and border authorities in different countries all over the world, security services, passenger and freight traffic services. The recognition of materials applied to the inspection control is traditionally understood as the comparison of materials the object is made of or fragments thereof by the effective atomic number and its associated parameters to one of the broad classes of compounds. All materials are divided into a number of classes, wherein each of the classes related to its range of variation of the effective atomic number is associated with its most common representative. The class of organic materials includes, for example, water, graphite, polyethylene, polypropylene and others, any of these materials can be selected as a typical representative of the class. A class of materials with a low effective atomic number is associated with aluminum. A typical representative of the class of metals and alloys with an average effective atomic number is steel. A class of materials with a high effective atomic number is associated with lead. At present, the recognition of materials of the inspection control of objects and their fragments are widely used for various implementations of the dual-energy method [1−7]. The inspection systems based on the betatron and linear electron accelerators are used to control large objects [8−11]. One possible way to improve the performance of inspection control is to scan vehicles with drivers. This approach leads to the formation of primary radiographic images for the object of inspection control at two levels of radiation dose: low level − to scan the cab with the driver; high level − to scan the rest of the vehicle. The low level is specified by the radiation safety standards. This implies the needs for experimental verification of the possibility of recognition materials and their fragments by high-energy dual-energy method for low levels of X-ray radiation dose.

Initial radiographic images were obtained using the inspection complex in Tomsk Polytechnic University for the energy pair 4 MeV−7.5 MeV. The inspection of test objects made of organic materials (water, plexiglas, nylon, wood), aluminum, carbon steel and lead was carried out to the mass range of 20 to 120 g/cm^2. The test object with the scanner is placed in the most problematic area − at a maximum distance from the axis of the beam of high-energy X-rays. For more accurate estimation of the parameters of calibration line, test objects are scanned at a speed of 4 cm/sec. The images were formed in the mode 1 low energy pulse and 1 high energy pulse. To confirm the basic hypothesis, at first we need to estimate the range of radiometric signal levels while reducing the absorbed dose of radiation, and then to investigate how the change affects the quality of recognition of materials of different classes − organic, aluminum, steel and lead.

2. The range of changes in the levels of radiometric signals reducing the absorbed radiation dose

Radiometric level signal is proportionally reduced with the decrease in dose rate. Deviation from this law is caused by two factors: inaccurate measurement of the absorbed dose rate and limitation of the betatron monitor by bit ADC. During the research the exposure dose of radiation beam axis P is reduced from 2.5 to 0.3 R/min. The dose rate in the scanning area is about 3.8 times less than in the center. Table 1 shows the values of radial thickness R1 and identification parameter Q. To simplify the analysis of the results presented in Table 1, the following color palette was used with the proper material recognizing fragments: blue − organic materials; green − aluminum and alloys; red − iron alloys; yellow − lead alloys. Incorrect recognition is marked in black. Averaging is performed over the entire area of the image fragment without boundary effects.

Table 1. Recognition of test materials fragments of objects while reducing the radiation dose.

Z	Material	*P*, [R/min] (center and periphery)							
		2.5 (0.665)		1 (0.266)		0.5 (0.133)		0.2−0.3 (0.053−0.08)	
		R_1	Q	R_1	Q	R_1	Q	R_1	Q
6	Polyamide (caprolon)	0.8358	0.74173	0.8304	0.74150	0.6948	0.67544	−	−
		1.5147	0.74150	1.5080	0.74171	1.3931	0.72513	−	−
		2.2135	0.73458	2.1776	0.73746	2.1611	0.73467	−	−
		3.3298	0.73276	3.2649	0.73820	3.2226	0.74645	−	−
	Tree (pine)	0.6847	0.74297	0.6775	0.74283	0.6824	0.74057	0.6749	0.76409
		1.2380	0.74122	1.2468	0.74158	1.2332	0.74395	1.2394	0.74658
		1.7785	0.73880	1.8002	0.73489	1.7643	0.74534	1.7477	0.74874
		2.2766	0.73612	2.2519	0.74585	2.2557	0.74369	2.2872	0.72867
		2.7822	0.73275	2.8065	0.73095	2.8207	0.72422	2.7406	0.73966
		3.2438	0.73483	3.3448	0.71376	3.2861	0.72531	3.1274	0.75144
13	Al	0.8433	0.76100	0.8468	0.76452	0.8095	0.76778	0.8280	0.77502
		1.5920	0.75800	1.6059	0.75613	1.5839	0.76285	1.5709	0.76999
		3.4022	0.76070	3.4525	0.77793	3.3567	0.78681	3.4578	0.77751
26	Fe	0.4861	0.77592	0.4858	0.76862	0.4882	0.76582	0.4860	0.77617
		1.1349	0.77681	1.1341	0.77426	1.1392	0.77319	1.1355	0.78386
		2.1109	0.78361	2.1142	0.78049	2.1050	0.78572	2.1058	0.78570
		2.9786	0.79258	2.9546	0.79686	2.9447	0.80301	2.9406	0.79857
		3.7536	0.80897	3.7200	0.81339	3.5561	0.8460	3.4689	0.87406
		4.3138	0.84531	4.2839	0.84658	4.1478	0.87807	3.7423	0.96352
		4.9245	0.85487	4.7050	0.89355	4.2663	0.98441	3.9855	1.03136

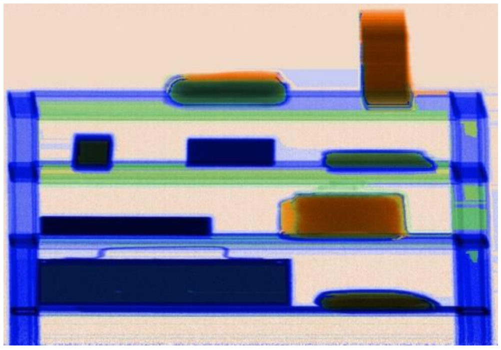
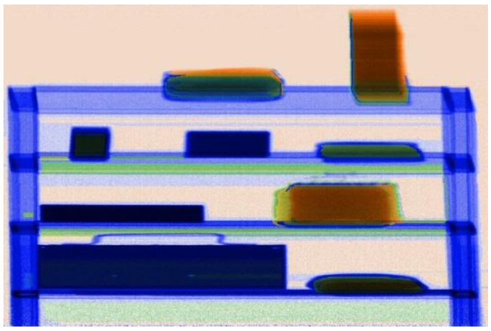
		1.5175	0.79454	1.5376	0.78604	1.5259	0.79097	−	−
		2.6269	0.83795	2.5956	0.804603	2.4109	0.90924	−	−
		3.0701	0.85022	3.0456	0.85394	3.0777	0.84960	−	−
82	Pb	3.5279	0.87392	3.4862	0.88427	3.5538	0.87221	−	−
		3.9120	0.89282	3.9170	0.88615	3.6936	0.87787	−	−
		4.5821	0.91246	4.4539	0.93654	4.3531	0.94519	−	−
		4.8774	0.95578	4.6305	1.00448	4.5391	1.01160	−	−

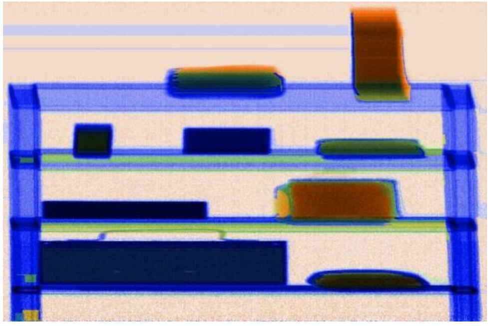
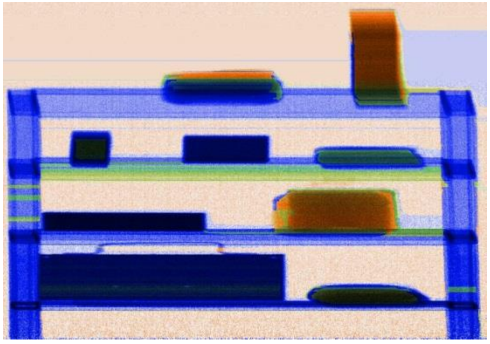
The analysis of the data from Table 1 makes it possible to conclude that the range of mass thickness fragments, for which you can confidently recognize the material of control object with the decrease in dose rate radiation, is narrow. When $P\approx0.266$ R/min, all the analyzed materials are confidently recognized in the range of mass thicknesses from 20 to 100 g/cm^2.

3. Experimental evaluation of recognition quality for the materials by dual-energy method (complex test objects)

The quality of recognition of the following materials was assessed experimentally: organic materials − flour, plexiglass, water; light metals and inorganic materials − aluminum, cement, salt; metals with the average effective atomic number − steel, copper; heavy metals − lead. The mass thickness of fragments was close to 40 g/cm^2. A total amount of 9 scan cycles for test objects were performed. In each cycle the dose rate varied –3 R/min; 2 R/min; 1 R/min; 0.5 R/min. Test objects from cycle to cycle had different mutual arrangement of fragments of various materials in height. The lower detector unit operated at lower levels of radiation dose rate than the central blocks. To illustrate this, the final images of the dual-energy method of test objects for 1 compilation are summarized in Table 2.

Table 2. The final images of test objects for 1 compilation.

Object	P_{max} [R/min]	Image
	3	
	2	

1	
0.5	

Images were obtained using a modified program Dual averaging window with 5 × 5 pixels, the minimum cluster size − 10 × 10 pixels. The images are painted according to the color scheme used by Heimann. A number of conclusions can be made based on the image analysis presented in Table 2.

1. With decreasing the dose noise levels of semi-tone pictures and color noise increase;
2. With a decrease in dose rate a significant part of the color fragments is disordered;
3. The distortions are more precise for the lower part of the image;
4. The boundary effects due to averaging and clustering appear mostly for pieces at the top of the test objects;
5. The size of the fragment, the material which is detected at the predetermined probability depends on the object's position by the vertical axis and its size in the direction of X-ray photons.

Table 3 shows the results of quantitative and qualitative detection of fragments of testing materials. The table shows the average values of effective atomic number of the material, the color to indicate numbers, and the class of materials.

Table 3. Quantitative and qualitative results of the detection of material fragments of test objects.

Material	Dose of radiation, [R/min]				Comment
	3	2	1	0.5	
Flour	10.2	10.4	10.4	10.8	Small size by vertical axis
Caprolon	4.5	4.5	4.0	4.0	
Water	6.0	6.3	4.9	6.1	
Cement	18.0	19.8	19.4	21.4	Correction recognition
Salt	16.4	16.3	16.0	19.4	
Aluminium	16.3	18.0	14.3	16.5	
Steel	24.9	25.7	24.0	26.3	
Copper	31.7	32.9	32.8	33.1	
Lead	51.9	53.3	49.5	52.2	

The results of the analysis shown in Table 3 prove the possibility to use the data on the effective atomic number of the material. Increase in the size of flour fragments in the scan direction substantially reducing the boundary effect leads to the correct recognition of the material fragments. The fact that the dose of X-radiation at the periphery is 2−3 times lower than in the middle of the beam allows making a conclusion about accurate recognition of the objects of material fragments of control with the decrease in dose levels of 0.25−0.3 to R/min. The information considered above is valid for proper cross fragment size of control objects and object fragments with thickness of about 40 g/cm^2.

4. Conclusion

The paper shows the main problems of recognition of materials of the object of inspection control by dual-energy associated with a decrease in the absorbed dose of radiation. It was proved that the radiometric range of the signal varies considerably, thereby reducing the thickness of the fragments, materials which are recognized with the given probability. This factor is the most significant for peripheral blocks of radiometric detector located at a considerable distance from the axis of the X-ray beam. The suggested invariant recognition method links the recognition of quality control and performance of testing object fragment area, the material which is recognized with the given probability. The experiments proved the possibility of a satisfactory recognition of materials of the object of inspection control at power levels of X-ray dose of about 0.25 R/min. The significant influence of boundary effects on the quality of recognition materials has been proved.

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