

## Innovative X-ray Backscatter Technique for Security Applications: Detection of Dangerous Materials

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### Abstract

Radiological inspections, in general, are NDT&E methods to detect the bulk of explosives without invasion into the object of analysis. In contrast to personal luggage, cargo or structural components constitute a complexity that may significantly hamper the detection of a threat by conventional transmission radiography. A novel approach of interrogating a large object to a certain depth only with a single sided access will be presented. It consists of an X-ray backscatter camera with a special twisted slit collimator for imaging backscattered objects. The new X-ray backscatter camera is not only imaging the objects due to their densities but also by taking into account the influences of surrounding objects. Additionally, it does not only image illuminated features but also depicts shadows from absorbing materials. This is a unique characteristic of the developed X-ray backscatter camera. Experimental mock-ups are conducted imitating container with threats among a complex packing as they may be encountered in reality. At the end, the significant advantages of the presented X-ray backscatter camera in the context of aviation and port security will be discussed.

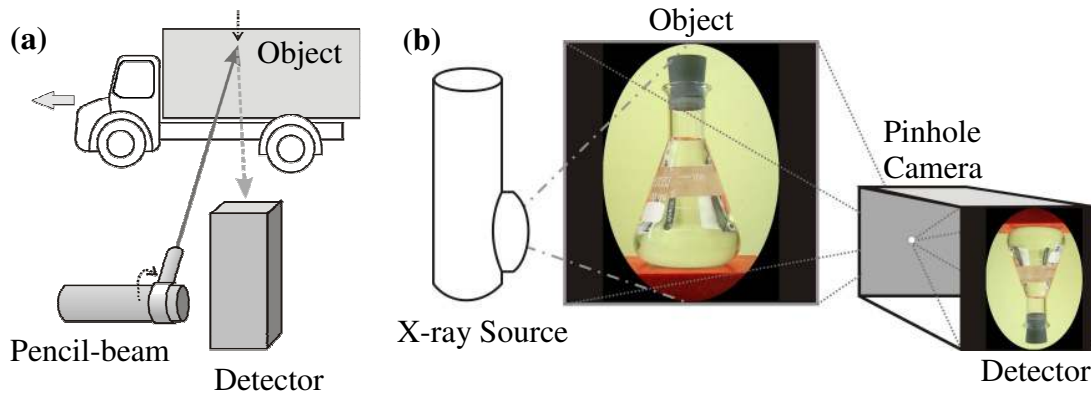
**Keywords:** X-ray backscatter imaging, irradiation geometry, detection of dangerous materials, security applications

### 1. Introduction

In contrast to X-ray transmission imaging, such as conventional radiography and computed tomography (CT), the X-ray backscatter technology (XBT) utilizes the scattered radiation caused by the Compton effect [1, 2]. The usual approach for X-ray backscatter imaging involves illuminating the object with a pencil-beam of known direction and collecting all the back-scattered radiation with large area detectors [3, 4]. Since the Compton effect depends on the electron density, low-Z materials are prone to exhibit X-ray backscattering while high dense matters such as heavy metals (eg. Fe, Cu, Pb, Ta, W) do not due to the photo-electric absorption.

The practical advantage of the XBT is to inspect an object from only one-side. This is particularly useful when an object with limited access points exists or when the interior of the object is complex in terms of overlaying details that a transmission image would be too difficult for the interpretation. There are specific cases where one-side inspection is only possible, especially for the inspection of an unattended baggage leaning against a wall or the inspection of a container with a complex packing. In this paper, we present an approach resembling the original idea of a pinhole camera suitable for high energy (> 500 keV) radiation with deep penetrating properties.

Figure 1 shows the difference between the conventional and the novel concept of generating a backscatter image. Commercially available systems for scanning large objects like containers or trucks are generally use the first principle, i.e. pencil-beam technique [4]. This technology utilizes a highly collimated beam of radiation and a high sensitive large area detector to inspect the objects and is available in commercial X-ray backscatter imaging devices [3, 4], as shown in Figure 1(a). The second principle of generating X-ray backscatter images is the illumination of a large area with a high kW X-ray source and a pinhole like camera encompassing a digital detector (see Figure 1(b)).



**Figure 1.** Principles of generating X-ray backscatter images using the (a) pencil-beam technique and (b) pinhole camera method.

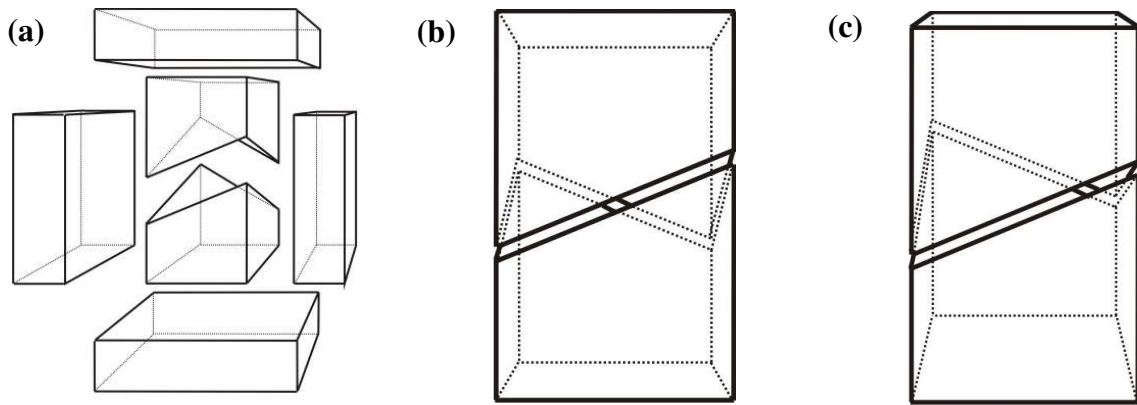
ComScan (Compton backscatter Scanner), a commercially available X-ray backscatter imaging system for NDT of aerospace components, was discussed by Harding et al. [5]. Here, a combination of a collimated X-ray source and a high resolution detector array equipped with slit collimators was used to record the backscattered radiation from the inspected object. The ComScan system is equipped with a commercial X-ray tube having energy 160 keV. The main limitation of the ComScan system is the fixed geometry between the radiation source and the detector, so the whole device scans the object plane by plane [6]. Based on the flying-spot technology, a mobile X-ray backscatter imaging system for the inspection of vehicles was discussed by Swift [7] and Schafer et al. [8]. This technology was also employed for the hidden contraband detection in persons [9]. Although flying-spot method has an advantage of fast inspection time, it requires large-area detectors to record the backscattered X-ray dose from the investigated object. In flying-spot methods, fixed irradiation geometry and a single viewing direction are the main limitations.

The developed X-ray backscatter camera in our work basically resembles the pinhole camera principle as shown in Figure 1(b). In the presented technique, a shielding in the cm range ( $\sim 5$  cm) is needed to attenuate any undesired beams to less than 1%. Previous investigations have proved that the radiography with digital detector arrays (DDAs) provides a high signal-to-noise ratio (SNR) of 100 times higher as compared to imaging plates even at a short exposure time [10, 11]. This main advantage of DDAs is considered in the presented X-ray backscatter technique. The aim of the presented study is to demonstrate the potential applications of the proposed X-ray backscatter technique to the aviation and port security. First, we present the imaging principle using the novel X-ray backscatter camera and a brief discussion on its construction. Second, we discuss the preliminary experimental X-ray backscatter imaging results on a miniature container model encompassing mock-up dangerous materials among a complex package.

## 2. New X-ray Backscatter Camera

### 2.1 X-ray Backscatter Imaging Principle

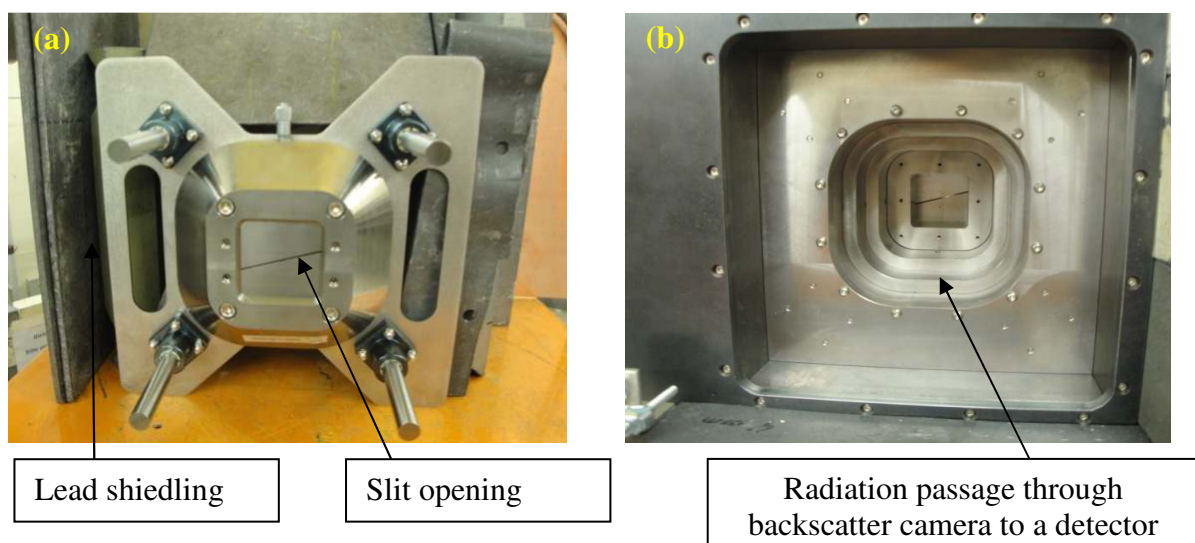
The new X-ray backscatter camera consists of a diaphragm with a virtual continuous series of holes in shifted direction which merge together forming a twisted slit, as shown in Figure 2 [12, 13, 14].



**Figure 2.** Schematic of the twisted slit collimator: (a) the gap is formed by the twisted surfaces of the upper and lower part of the collimator, (b) the intersection of the front and back side of the slit forms the beam passage and (c) when tilting the aperture to the front, the beam passage is shifted to the right.

This approach results in a large angular aperture with a wall thickness adequate to shield hard radiation like high-energy X-rays ( $> 0.5$  MeV) or even gamma rays emitted by gamma sources such as  $^{60}\text{Co}$  or  $^{137}\text{Cs}$ . Figure 2 shows the schematic of the twisted slit collimator in two different tilted positions. On the front side the slit is inclined into one direction and on the back side into the opposite one (Figure 2(a)). In addition, the inside of the slit is lined with ruled surfaces. Consequently, the linear passage through the slit is possible only through a hole-shaped gap along the thickness direction, as shown in Figures 2(a), 2(b) and 2(c). A detailed geometrical description of the beam passage through the collimator for different incident directions was presented in [12].

The developed portable X-ray backscatter camera, weighing 30 kg, is shown in Figure 3. It consists of a housing constructed from tungsten (W) to fulfil the requirements such as reducing the undesirable radiation from surroundings. The image sharpness and brightness can be controlled by varying the slit opening as it can be seen in Figure 3(a). In addition, the present design of the new X-ray backscatter camera requires some additional lead (Pb) shielding in order to protect the detector electronics.



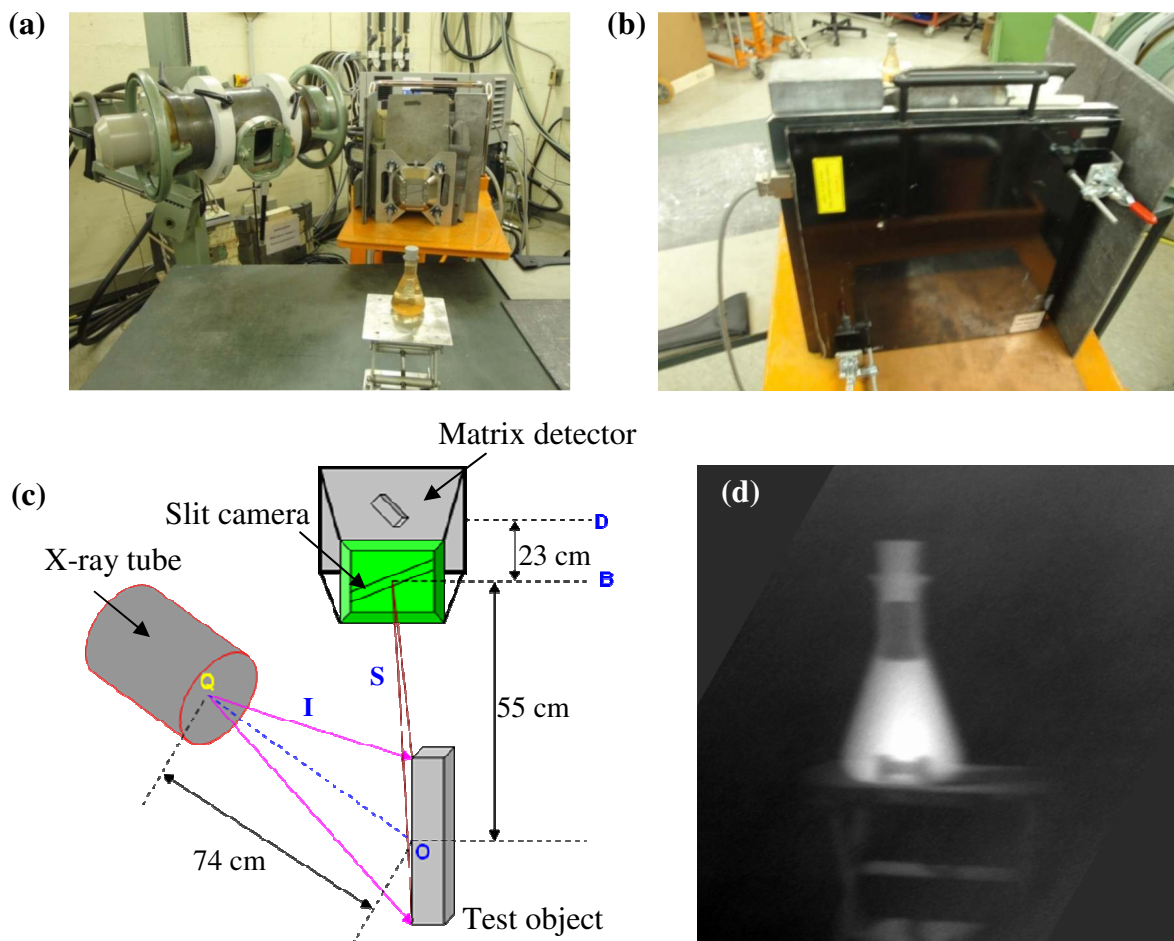
**Figure 3.** Photograph of the constructed X-ray backscatter camera (a) front view, (b) internal construction.

### 3. Experimental Results and Discussion

#### 3.1 Experimental Setup and Data Acquisition

The experimental setup for X-ray backscatter imaging of an object is illustrated in Figure 4. In this case, an Erlenmeyer flask is used and it is filled with water, covered a rubber bung on the top and included a steel (Fe) bolt at the bottom. In general, the object to be detected will be located inside of a piece of luggage or cargo-container. An industrial X-ray tube (GE ISOVOLT TitanE) with a maximum voltage of 420 kV and tube current of 10 mA is used for the experiments. The X-ray backscatter camera equipped with a digital flat panel detector (VIDISCO Rayzor-X) was used to record the backscattered X-ray dose from the inspected object (see Figure 4(a) and 4(b)). The detection area of the flat panel detector is  $22.2 \times 22.2 \text{ cm}^2$  and it has an image resolution of 3.5 lp/mm. The flat panel detector consists of  $1560 \times 1560$  pixels with a pixel size of  $143 \mu\text{m}$ .

In the current X-ray backscatter imaging, the image area on the detector is limited by the collimator geometry which depends on the slit geometry, particularly on its width. The backscattered signals were acquired using digital X-ray imaging software (XbitPro) [15].



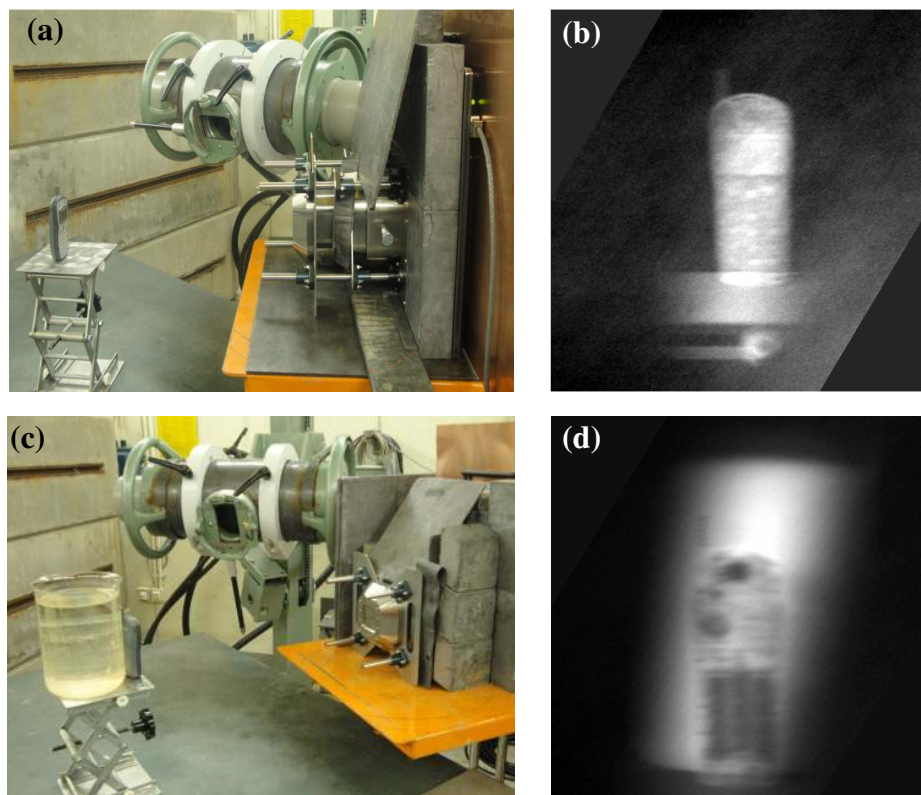
**Figure 4.** (a) Experimental setup used for X-ray backscatter imaging, (b) high-resolution digital flat-panel detector, (c) schematic illustration of the X-ray backscatter technique and (d) a typical X-ray backscatter image using the novel twisted slit camera. I, S represent the incident and scattered X-rays.

The schematic of the geometry of the experimental setup is shown in Figure 4(c). A typical X-ray backscatter image using the presented twisted slit collimator is shown in Figure 4(d). In this case, a simple object of an Erlenmeyer flask can be seen, which is filled with water and covered a rubber bung on the top and a steel (Fe) bolt inside at the bottom (see Figure 4(d)). In total, four exposures, each with 3 minutes duration, were integrated for obtaining high SNR in the X-ray backscatter image.

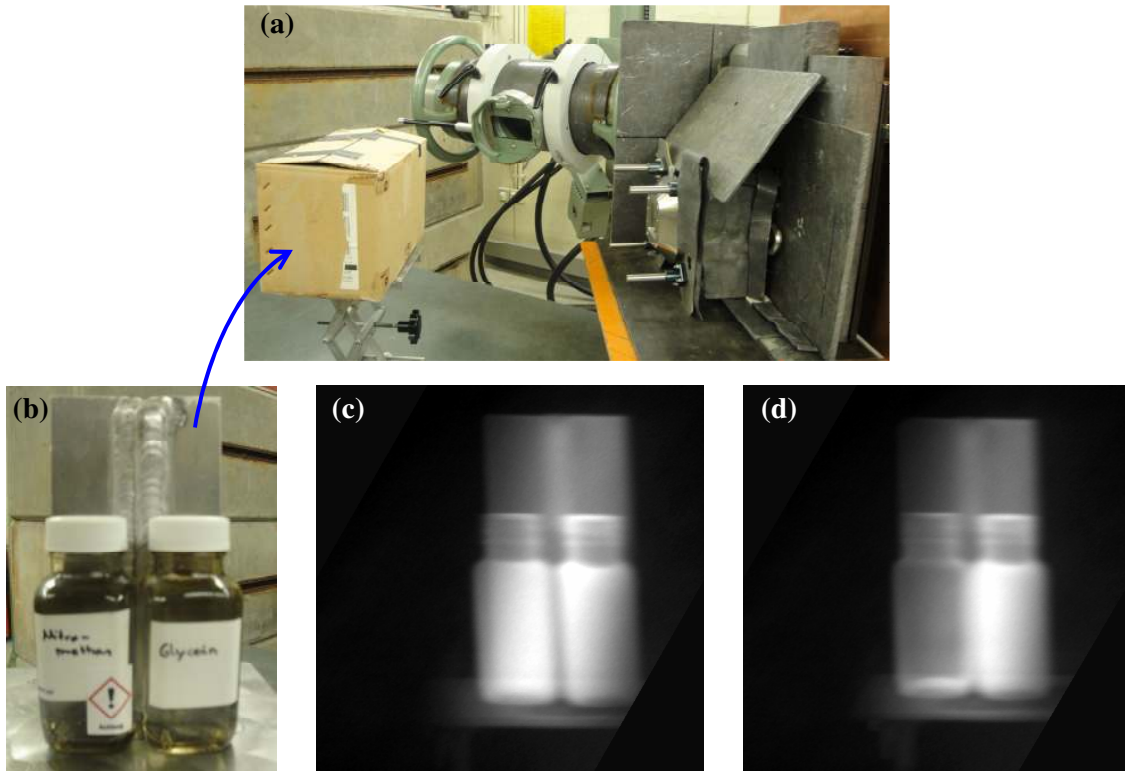
### 3.2 Application to Aviation and Port Security

A potential application of the proposed new X-ray backscatter technique can be imagined within the aviation security for the inspection of luggages or cargo to identify suspicious details and putative dangerous liquid materials, especially for objects permitting a single sided access. Figure 5(a) shows the experimental setup used for inspecting a mobile phone without any backscattering background. A slit width of 0.8 mm was used for allowing back-scattered radiation from the inspected object through the X-ray backscatter camera. The obtained X-ray backscatter image is shown in Figure 5(b). It can be seen in Figure 5(b) that the internal features of the mobile phone without backscattering background are not obvious due to the X-ray scattering only from the outer shell.

In order to study the influence of surrounding objects on the backscattered image, a mobile phone was placed in front of a low-atomic-number ( $Z$ ) material such as water ( $H_2O$ ) (see Figure 5(c)). The obtained X-ray backscatter image is shown in Figure 5(d). It can be seen from this image that some internal features of absorbing materials within the mobile phone are apparent as silhouettes.



**Figure 5.** (a) Photograph of the experimental setup, (b) experimental X-ray backscatter image of a mobile phone using 420 kV X-ray tube voltage, 10 mA as tube current, 3 min of exposure time. (c) Photograph of the experimental setup to inspect mobile phone in front of the water filled flask, (d) backscatter image of the mobile phone in front of the water filled flask.



**Figure 6.** (a) Experimental setup, (b) arrangement within the cotton container and (c) X-ray backscatter image of a cotton container containing nitromethane and glycerin bottles with a 10 mm thick aluminum (Al) weld in the back using 420 kV X-ray tube voltage, 10 mA as tube current, 3 minutes of exposure time and slit width of 1 mm. (d) same as in Figure 6(c) but the nitromethane glass bottle is replaced by an empty glass bottle.

Another potential application of the presented X-ray backscatter technique is in screening cargo-containers where threats have to be detected efficiently among a complex packing. As an illustration, Figure 6(a) shows the experimental setup used for inspecting a cotton container with dimension  $30 \times 15 \times 18 \text{ cm}^3$ . The mock-up comprises dangerous materials such as nitromethane ( $\text{CH}_3\text{NO}_2$ ) on the left and on the right, as precursor for the explosive materials, glycerin ( $\text{C}_3\text{H}_8\text{O}_3$ ) which are filled within small glass bottles (see Figure 6(b)).

Figure 6(c) shows the X-ray backscatter image of the investigated object. It can be seen from Figure 6(c) that the glass bottles containing dangerous liquids are clearly identifiable even in complex packages encountered in the reality. In the obtained X-ray backscatter image, two different liquid materials with similar densities appeared with the same intensity (i.e. grey value). Figure 6(d) shows the backscatter image of an empty glass bottle on the left and a glass bottle with glycerin on the right that are placed in front of the Al weld plate. The proposed X-ray backscatter technique was able to distinguish between liquids and solids.

In this paper, we presented the qualitative results obtained by analysing the X-ray backscatter images. For quantitative analysis, it is further important to consider the geometrical loss of scattered radiation within the X-ray backscatter camera and also other scattering effects due to image sensors in the digital detector. While the proposed technique can distinguish between liquids and solids, our future research work at BAM would like to address the issue of quantifying the material composition using the dual-energy X-ray backscatter technique.

## 4. Conclusions

The new X-ray backscatter technology (XBT) provides an alternative approach for inspecting luggages and screening containers with a single sided access. The developed twisted slit collimator efficiently resolved the problem of providing a pinhole-camera like imaging system for high-energy ( $> 500$  keV) radiation with deep penetrating properties. We showed that, depending on the illumination geometry, it is possible to identify the internal features of absorbing materials by taking into account not only density variations but also influence of the surrounding objects. Experimental mock-ups were designed to imitate threat objects in luggage and dangerous materials in cotton containers with complex packaging. The potential applications of the presented X-ray backscatter technique to the aviation and port security were demonstrated. The quality of the X-ray backscatter image was improved by utilizing the applications of high-resolution digital detector arrays (DDAs). The primary experimental results on X-ray backscatter images of miniature cotton containers showed that this technology is able to distinguish liquids and solids amidst a highly heterogeneous packing. Currently, the construction of the multiple-slit camera for X-ray backscatter imaging is under development. This technology allows us to obtain enlarged X-ray backscatter images of objects recording more scattered dose by using a small exposure time. X-ray backscatter tomography using the novel slit camera for security applications is planned as a part of the future work.

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