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Augmented X-rays: new functionalities for High energy X-rays Cargo scanner

Serge Maitrejean[1], Thi Xiu Le[1, *], Khanh Hung Tran[1], Najib Gadi[1], Abdellatif El-Jaafari[1], Benoit Beaurepaire[1]
[1] Smiths Detection France, 36 Rue Charles Heller, 94405 Vitry sur Seine, France
(*) thi-xiu.le@smithsdetection.com

***Abstract* — X-ray radioscopy at high energies (MeV) is a widely used technique for non-destructive inspection of cargo containers and trucks at ports and borders. Dual-energy imaging is an established method for cargo material discrimination, that works by estimating the average effective atomic number of penetrated objects along each X-ray path, based on the energy dependent mass attenuation coefficient of materials. However, due to 2D nature of the radioscopy image, it is currently difficult to understand how the objects are positioned in the cargo depth and material discrimination interest is limited when objects of different natures are superimposed along X-ray paths. In this article, we describe four totally new imaging functionalities which have been developed and validated by end-users during field tests. These functionalities, under a generic name Augmented X-rays (AXR), are based on the use of multi-column detectors (called Matrix detector) and new algorithms for the material discrimination. They are comprised of in-depth information, image stabilization, wall removal (removing of metallic objects) and de-overlapping of material discrimination. These functions help in pushing the current 2D cargo inspection close to pseudo 3D by localizing on which depth planes are the objects (either close to the accelerator or the detector) and extends the usefulness of material discrimination by discriminating objects one-by-one, helping ease the identification of low atomic number objects (explosives, drugs, cigarettes…).**

***Keywords* — Augmented X-rays, cargo inspection, depth information, advanced material discrimination.**

I. Introduction

CUSTOMS since the 90s, have used high energies X-ray scanners as a routine inspection tool for detecting smuggling or tax fraud in trucks at terrestrial borders or in containers at ports. Dual-energy systems allow for the discrimination of materials within cargo by estimating equivalent atomic number and material density based on the exponential attenuation law of X-rays, relating the transmitted intensity to the material attenuation coefficients. Different material discrimination algorithms exist such as α-curve, R-curve, H-L curve methods [2-4]. Recently, some studies tried to address the material discrimination for overlapped objects in cargo via virtual peeling method [5-6] but some prior knowledges of material objects inside the cargo were needed.

Until now, the current used technique is still 2D X-ray radioscopy. In this work, by using several-column detectors and a reconstruction algorithm, a kind of pseudo 3D image (2D X-ray image combined with depth information on object contours) can be obtained (in-depth information). In addition, X-ray image deformation due to unwanted motions can be stabilized by correcting "wave" artefacts. Furthermore, a new material discrimination method has been proposed so that we can not only have an instant view of objects made of organic and low atomic number in the cargo (wall removal) but also do the material discrimination for objects one by one even when screened by other materials (de-overlapping).

II. Methods

A. Methods based on the use of Matrix detector

Matrix detector is a type of detector comprising of several side-by-side columns of detection (Fig. 1 a). Fig. 1 b shows an example of image made of n pulses where each pulse containing 5 columns of data with a slight difference of scanning angle between these 5 columns.

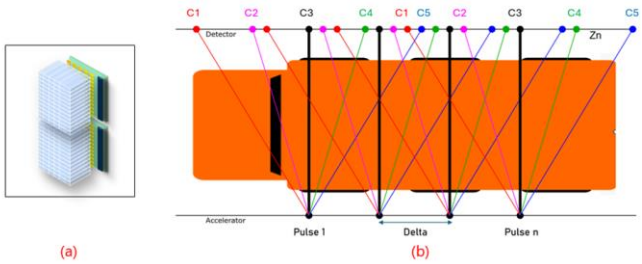

Fig. 1. Matrix detector (a); Principe of X-ray image made of multi-column detectors (b) where Delta is the distance between 2 consecutive pulses and C 1-5 are 5 detection columns.

1) Image reconstruction method and in-depth information

When data from different detection columns are simply put side by side, some artefacts can be observed on the image at the zones around the contours of objects due to the viewing angle difference. This happens when the displacement between two pulses is lower than the detector's width: an object can be seen several times by different detection columns at different pulses (Fig. 1 b). This effect, like stereoscopy at very low angles, is dependent on the depth of the objects. Therefore, to correct for these artefacts, the depth at which the objects are located must be estimated. This is done via a total variation minimization among all images reconstructed at different cargo depth planes. It provides us with a final image free of artefacts as well with a map of object depth positions within cargo.

2) Image stabilization

In general, two types of scanning mode are possible: mobile mode, where the scanner moves alongside stationary cargo, and passthrough mode, where cargo moves alongside the stationary scanner. The oscillations of the boom containing the detectors during the mobile scan, or uneven scanning ground used for the passthrough scans, spawn waves on the image. Based on the redundancy of the information given by different detection columns (Eq. 1) and using an energy minimization technique, the amplitude of the displacement can be estimated for each pixel in the image and therefore distortion effects can be corrected. The energy to be minimized is of the type:

$$E_T\left((\delta_x)_{ij},(\delta_y)_{ij}\right) = \sum_{\substack{n,p\\p>n}} E_C\left(n,p,(\delta_x)_{ij},(\delta_y)_{ij}\right) + \alpha\left(\sum_{ij}(\nabla^2(\delta_x)_{ij} + \sum_{ij}(\nabla^2(\delta_y)_{ij}\right), \quad (1)$$

With $E_C\left(n,p,(\delta_x)_{ij},(\delta_y)_{ij}\right) = \sum_{ij}(I_p\,(i-(p-n)(\delta_x)_{ij}\,, j-(p-n)(\delta_y)_{ij}) - I_n(i,j))^2$

where (n, p) are 2 different detection columns among all detection columns (e.g. 5 in Fig. 1) and $((\delta_x)_{ij},(\delta_y)_{ij})$ are displacements between two adjacent pixels. The optimization constraint in Eq. 1 is since these displacements are regularly quite small.

B. New material discrimination method: the equivalent mass

The material discrimination is an estimation of atomic number based on energy dependency of mass attenuation coefficient. Practically, we use 2 energy spectrums which are emitted alternatively from pulse to pulse: High Mode (HM) & Low Mode (LM), for example 6 and 4 MeV. For each pixel of an X-Ray image, equivalent atomic number is calculated using different kinds of curves measured during a calibration phase as $-\ln T(E_{HM})$ vs $-\ln T(E_{HM}) + \ln T(E_{LM})$ (α curve: [2]); $-\ln T(E_{HM})$ vs $\ln T(E_{HM})/\ln T(E_{LM})$ (R curve: [3]) and $T(E_{HM})$ vs $T(E_{LM})$ (H-L curve: [4]) where T and lnT are transparency and logarithms of transparency. Despite the calibration phase, these curves stay highly non-linear for each material which makes them difficult to handle for more than estimating the average atomic number.

In this study, to obtain a quasi-linear representation of the material discrimination to facilitate the material decomposition of overlapped objects, we introduce a new material discrimination method called the equivalent mass. The main principle (Eq. 2) is to calculate for a chosen reference material (ref), an equivalent mass so we can achieve the same value of transparency by using the same energy spectrum (E).

$$T_r(M,Z,I) = \int_0^{E_{max}} I(E)e^{-\frac{\mu}{\rho}(E,Z\ \ )M}dE = \int_0^{E_{max}} I(E)e^{-\frac{\mu}{\rho}(E,Z_{ref})EqM}dE\ , \quad (2)$$

With M, Z, I are respectively mass and average atomic number crossed by X-rays and energy spectrum.

Like other material discrimination methods, a calibration phase of different materials (e.g. PMMA, Al, Fe, Pb) is needed. One of the calibrated materials is chosen as a reference material, and we plot the curves $(EqM_{HM} + EqM_{LM})/2$ vs $(EqM_{HM} - EqM_{LM})$ for all calibrated materials. Fig. 2 shows the calculation concept of the equivalent mass where for the reference material, i.e., steel $(EqM_{HM} - EqM_{LM})$ is zero and its curve lies on X axis. Note that experimental curves are quasi-linear.

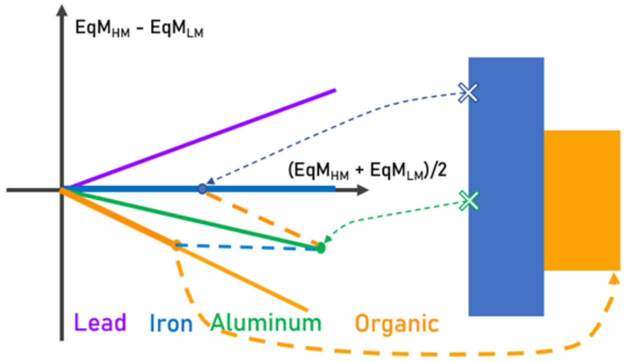

Fig. 2. The equivalent mass's schematic curves and the principle of atomic number's estimation of superimposed zones based on the quasi-linearity of the equivalent mass.

1) Wall removal

An image free of the reference material can be displayed by calculating $(EqM_{HM} - EqM_{LM})$ for each pixel. This is like the clinical dual-energy application where X-ray radioscopy image of human body was discomposed into bone and soft-tissue images [7-8]. By thresholding this image, it is possible to have a direct view of low atomic number objects (when the reference material is Aluminium or Iron). This possibility is named wall removal, as, in the case of containers for example, it removes digitally the container wall.

2) De-overlapping

As current material discrimination gives an average result on the whole thicknesses crossed by X-Rays, it doesn't directly discriminate objects, but only the superimposition of objects: e.g., a superimposition of an organic with steel objects can appear as aluminium. Based on the additive/quasi linear property of the equivalent mass (Fig. 2, the vector corresponding to the superimposition of two objects - the green one, is very close to sum of the two vectors representing the superimposed objects – the blue and the yellow ones) and an advanced segmentation process, it becomes possible to subtract, for each individual object in a cargo, all other objects which are superimposed, and to estimate its atomic number.

III. Results

A. In-depth information

As aforementioned, the objective of the in-depth function is to give the operators an estimation of how different objects are positioned in the cargo's depth. Fig. 3 shows an example of a cargo image where around the object's contours, different colours are added depending on their depth position in the cargo: red when objects are close to the accelerator, yellow-green when objects are in the middle of the cargo and blue when objects are close to the detector. From this in-depth information, the users can easily understand how the objects are positioned inside the container, helping to find the suspicious objects if needed. This is instrumental in shortening time required for a manual check of the cargo and fostering a better understanding of the cargo content.

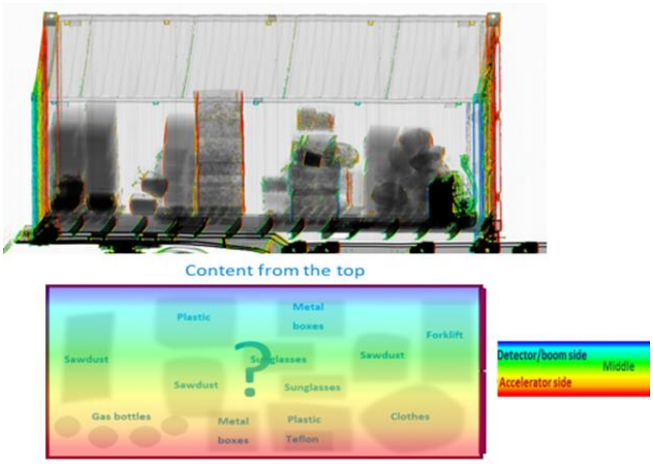

Fig. 3. Result of In-depth information. On top: the transmission image with the depth information displayed as the colour scale and Bottom left: the interpreted cargo content view from the top.

B. *Image stabilization*

Fig. 4 shows an example of a cargo image before (Fig. 4 a) and after stabilization (Fig. 4 b). In the corrected image, straight edges of objects appear as straight lines and no more waves can be seen on the top of the cargo, making the image more readable for the operators.

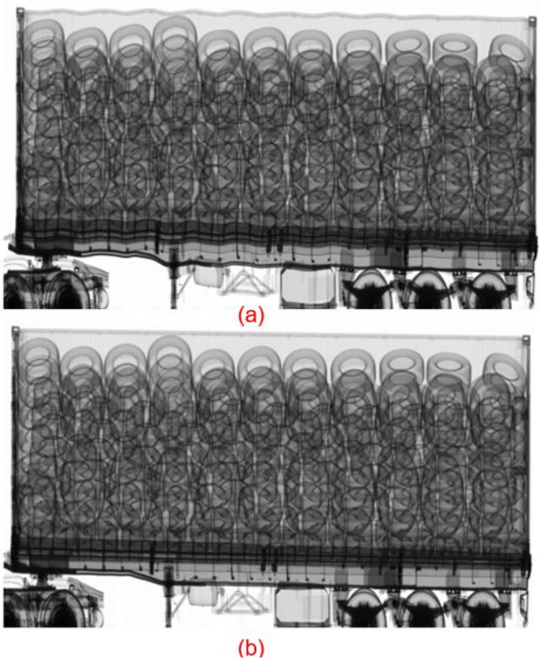

Fig. 4. Effect of Image Stabilization, (a) before and (b) after image stabilization.

C. *Wall removal*

Fig. 5 a shows an example image of a cargo filled of different objects made of different materials. This image was obtained during a European project - ENTRANCE's testing campaign. The corresponding wall removal image with Iron as reference material (Fig. 5 b) highlights cargo zones containing only objects with low atomic number (organic or intermediate materials), making the detection of drugs or explosives smuggling easier. The intensity of the wall removal image reflects the quantity (thickness) of low atomic number objects.

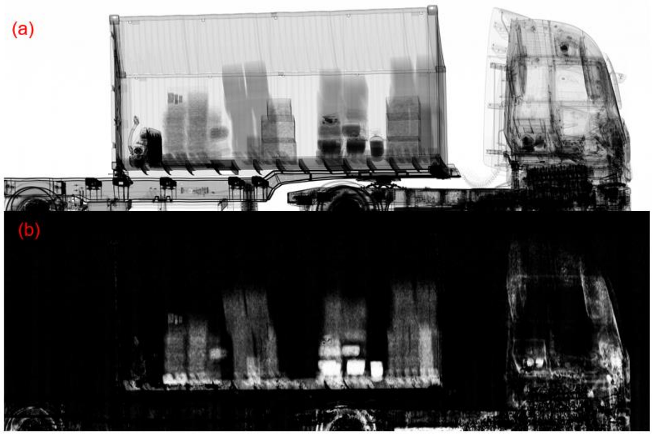

Fig. 5. Transmission image (a) and Wall Removal image (b) of the same truck.

D. *De-overlapping*

Fig. 6 a shows an image of the experimental setup where three bags of 1-kg of sugar (organic materials) were placed in different positions behind some centimetres of steel. By looking at its normal high energy discrimination image (Fig. 6 b), we can see that the background zone is made of steel (coloured as blue) while for the superimposed zones of steel screen and sugar bags, they are recognized as intermediate materials (coloured as green), corresponding to the definition of the equivalent atomic number of the whole thickness crossed by X-rays. By doing de-overlapping, as shown in Fig. 6 c & d, the superimposed zones are decomposed into 2 correct pure materials (organics – sugar bags coloured as orange and steel – the screen coloured as blue).

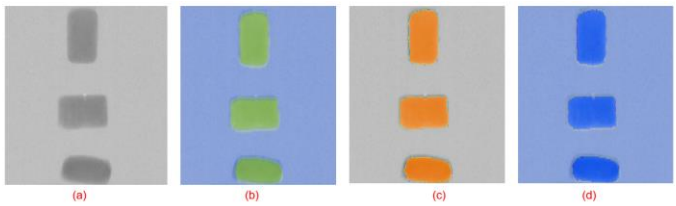

Fig. 6. De-overlapping of 1-kg sugar bags behind a steel screen with: Transmission image (a); results of Material Discrimination (b) and De-overlapping results (objects – sugar bags and the steel screen respectively: c, d).

E. *Combination of different AXR functions*

The four different functions of AXR (in-depth information, image stabilization, wall removal, de-overlapping) can be combined to fulfil the ultimate objective of the operators to check quickly and correctly the passing cargos. Fig. 7 shows a combination of in-depth and wall removal results. By looking at this image, the operators can have a quick idea of whether organic materials (suspicious materials) are placed in the cargo and where are they in the cargo's depth.

IV. Conclusions

In this article, we present four new imaging functionalities collectively referred to as AXR that can become a tool for customs organization to improve the efficiency of X-ray scanning practice and to reduce the time of manual checking:

- In-depth information is instrumental for a better understanding of cargo contents and necessary to know on what side of cargo are the threats;
- Image stabilization corrects unwanted deformation on X-ray images;
- Wall Removal gives an instant view of objects made of organics and low atomic number, therefore proving Backscatter-like images;
- De-overlap helps to discriminate objects one by one and not their superimposition, therefore, to extend the material discrimination usefulness.

Furthermore, the operators can combine different functions of AXR to refine the understanding of cargo contents.

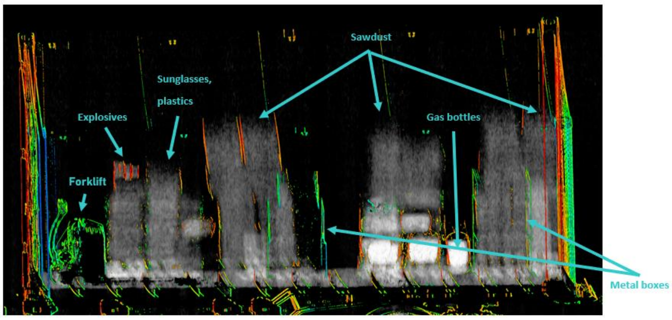

Fig. 7. Combination result of In-depth information and Wall Removal of the same container as Fig. 5.

Appendix

These works have been patented, the readers can find more information from [9-11].

Acknowledgment

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