DTU Library

Opportunities and challenges of implementing energy dispersive x-ray CT in aviation security screening

Sloth, Steffen; Olsen, Ulrik Lund; Quagliotti, Danilo; De Chiffre, Leonardo; Christensen, Morten; Poulsen, Henning Friis

Published in:
E-Journal of Nondestructive Testing & Ultrasonics

Link to article, DOI:
10.58286/27708

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Opportunities and challenges of implementing energy dispersive x-ray CT in aviation security screening

Steffen Sloth[1,3], Ulrik L. Olsen[1], Danilo Quagliotti[2], Leonardo De Chiffre[2], Morten Christensen[3], Henning F. Poulsen[1]

[1]Department of Physics, Technical University of Denmark, Fysikvej 1, 2800 Kongens Lyngby, Denmark

[2]Department of Civil and Mechanical Engineering, Technical University of Denmark, Koppels Allé Building 404, 2800 Kongens Lyngby, Denmark

[3]Exruptive A/S, Højnæsvej 75, 2610 Rødovre, Denmark

Abstract
This work presents opportunities and challenges in energy dispersive CT systems for aviation security applications. Current security x-ray scanners use dual-energy systems for threat identification. Dual-energy scanners cannot clearly separate all materials, which results in high false-alarm rates and cause delays for travellers. The development of both new energy dispersive photon counting detectors and associated analysis algorithms allows for improved threat detection by employing energy dispersive scanner systems. The implementation in aviation of such systems as security x-ray scanners also poses several challenges, which are discussed in the paper.

Keywords: Aviation security x-ray screening, MECT, 3D material characterisation, Fixed gantry systems.

1 Introduction

During the last decade, x-ray scanners in airports have evolved from using multi-view dual-energy systems into dual-energy x-ray computer tomography (CT) systems. Dual-energy systems generate two data sets of the object under inspection (e.g. luggage) using two different but overlapping x-ray spectra [1, 5]. From the two data sets, and given the two initial energies, the effective atomic number (Z_{eff}) and effective density (ρ_{eff}) can be estimated and used for material classification [9].

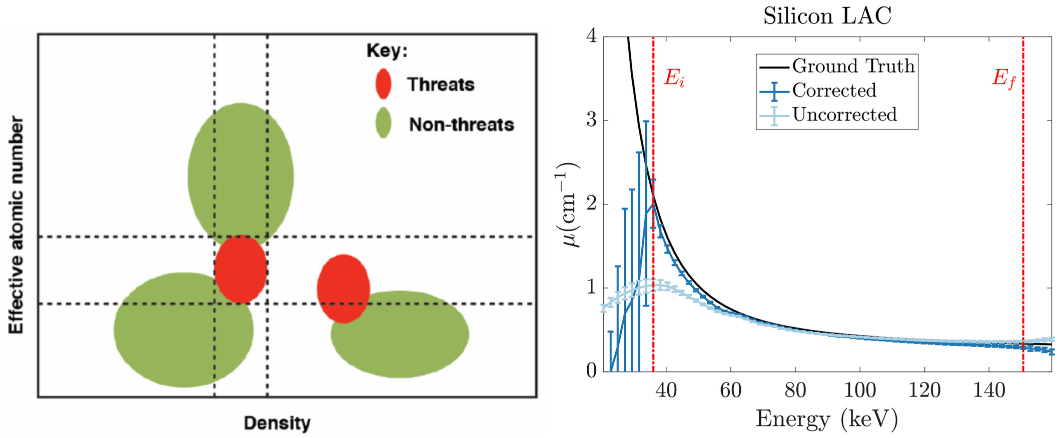

Figure 1: Dual-energy scanners distinguish between materials from estimates of the effective atomic number (Z_{eff}) and effective density (ρ_{eff}). The left panel illustrates a 2D map of threats and non-threats [27]. Energy dispersive scanners can extract a linear attenuation coefficient (LAC) for each material as a function of x-ray energy, as seen in the right panel for silicon [4]. The measured LAC might need to be spectral corrected, as discussed in section 3.1.1, to be comparable with a material ground truth, here calculated using cross-sections provided by the NIST database. From the LAC the Z_{eff} and ρ_{eff} can be extracted (e.g. by fitting) within the lower and upper thresholds E_i and E_f, respectively. The two energy thresholds excluded regions with low photon statistics and pulse pile-up [4].

Dual-energy is the established technique used for decades in security x-ray scanners. Yet, the technique cannot clearly separate all benign artefacts from threats [27], as illustrated by the overlapping regions in figure 1 (left panel). To safely identify all threats some benign artefacts must be falsely classified as threats, thereby, increasing the number of false alarms, which is a large contributor to delays at airport checkpoints.

The development of solid-state energy dispersive x-ray detectors over the last decade opens up the possibility of improving material classification [4–6]. By detecting the x-ray's energy an absorption spectrum for each material can be obtained [5, 6, 16],

https://doi.org/10.58286/27708

as illustrated in figure 1 (right panel), which increases the amount of information available for material classification. The development in energy dispersive detection has especially led to publications and innovation for medical CT scanners [17, 18, 21, 22]. In medical applications besides the ability to separate materials, energy dispersive detection offer improved contrast at low-doses and a more uniform weighing of the x-ray spectra among other advantages [16–18, 21, 22]. However, implementing energy dispersive detectors in a scanner also comes with a series of challenges [16–18].

This paper will highlight the requirements in security x-ray scanners as compared to medical CT in section 2. The fundamentals of an energy dispersive detection system are explained in section 3, together with the associated challenges and opportunities of energy dispersive computer tomography (MECT). Section 4 will discuss opportunities and challenges of implementing energy dispersive detectors in aviation security x-ray scanners.

2 Requirements for aviation x-ray security vs. medical scanners

Medical imaging and CT scanners are generally interested in achieving high-resolution images with high contrast between different regions, e.g. between tissue and bone, acquired with the lowest possible radiation dose [17, 18, 21]. Energy dispersive detectors are interesting because they offer a small pixel size (high spatial resolution) and the ability to extract more information from each x-ray passing through the patient by determining the x-ray energy. Determining the photon energies has been shown for several applications to improve contrast at an equivalent dose [17, 18, 21].

For aviation security, the interest in energy dispersive detectors is different. Here the focus is on the ability to achieve an improved material classification of luggage content. The legislation for an airport depends on the specific country and the macro geographical region it belongs to. Most countries in Europe together with a series of partner countries follow the ECAC regulation [28], while North America follows the TSA and CATSA regulation [30, 31]. Most of the other countries follow their own regulations and legislation, which usually are inspired by the ECAC and/or TSA regulations.

The detection of bombs in cabin luggage is usually done by material classification of the explosive compounds within the device. Both the ECAC and TSA/CATSA regulation state a specific list of explosive compounds and precursors, which an explosive detection system (EDS) needs to be able to detect [29–31] (the lists of threats and detection thresholds are confidential). The task of a security scanner is to safely identify any prohibited item in the luggage. From a metrology point of view, this creates a challenge since the measurands are poorly defined in terms of object shape, size, and material composition. Nonetheless, energy dispersive detectors especially offer improvements in material detection and classification [5, 6].

Typically, a state-of-the-art scanner in aviation security can handle an average throughput of around 150 passengers per hour. Ideally, the time spent on each passenger's set of luggage should not exceed thirty seconds, including the operator's intervention in examining the presence of threats. The augmented information by the energy dispersive scanners in each acquisition can support the operator's decision-making process, despite several challenges. Both the data acquisition and decision-making processes are significantly more pressed on time than what is common in medical science.

3 Opportunities and challenges using energy dispersive detection

Historically, three types of energy dispersive detectors exist: gas-detector, scintillators, and solid-state semiconductor-based [16]. Solid-state energy dispersive x-ray detectors are photon counting detectors (PCD) they became commercially available during the last decade and were tested in various research implementations [5, 6, 16, 20, 21, 24, 25]. The latest development of semiconductor-based PCDs has led to detectors able to operate with a high flux intake ($\sim 1 \times 10^8\,\mathrm{counts/cm^2/s}$), which is required for most industrial implementations including aviation security [17, 18].

This section will first explain the fundamentals of photon counting detectors, secondly discuss the challenges associated with correcting the spectral response of an energy dispersive PCD, and thirdly outline the opportunities for improving the algorithms for material classification.

3.1 Fundamentals of energy dispersive photon counting detectors

The most used x-ray detector for high-resolution imaging is the scintillator based detector, which uses a scintillating material to convert high energy x-rays into several photons of lower energy. Typical scintillators emit the photons in the visible range of the spectrum and conventional optical camera sensors are used to detect these photons. [16–18]. In energy dispersive photon counting detectors, the x-ray photons are instead converted directly into an electrical signal [16, 17]. This is achieved by using a solid-state semiconductor crystalline detection media with high x-ray absorption. This media is usually Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CdZnTe), Germanium (Ge), or Silicon (Si) [16, 18, 21]. The crystal is enclosed between a monolithic electrode (cathode) and evenly spaced pixelated electrodes bonded on the application specific integrated circuit

(ASIC) [16], see figure 2. An electrical field is applied across the detector crystal. When an incident x-ray photon interacts with the detector crystal a cloud of electron-hole pairs is generated. The electron cloud will drift towards the positive bias of the external electrical field[16]. The movement of the electron cloud will induce a transient current in the electrodes. The transient current is picked up by the ASIC and processed through a charge-sensitive-preamplifier [16]. The amplitude and time width of the detected signal is proportional to the size of the electron cloud and proportional to the deposited energy of the initial incident x-ray photon [16–18]. The hole cloud is not detected since the energy resolution would be worse than the electron cloud due to the lower mobility of the holes. This also eliminates the need for detection electrodes on the front side of the crystal, which otherwise would interfere with the incident x-rays.

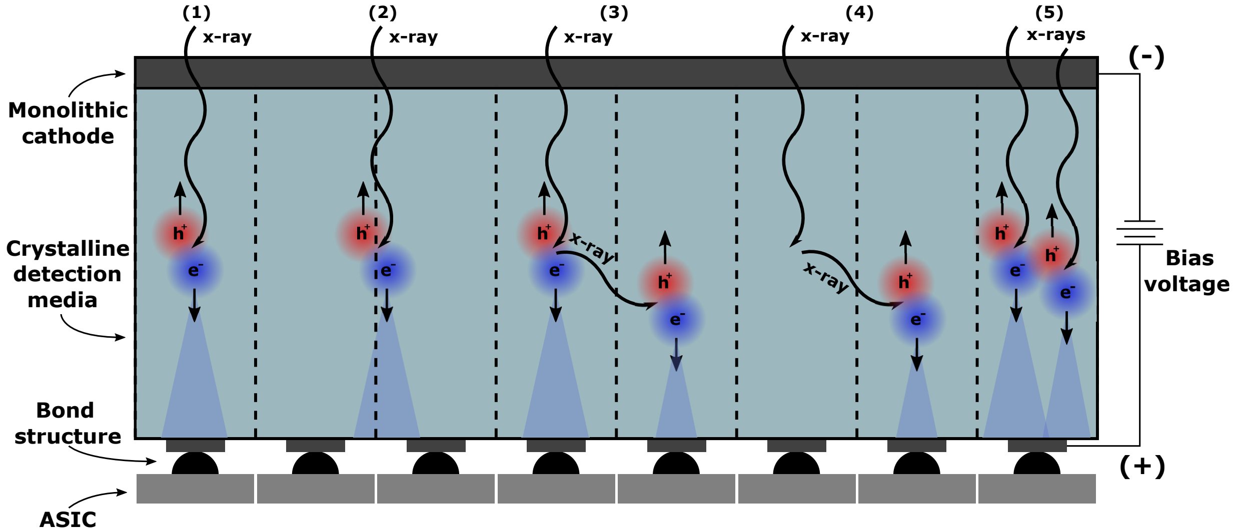

Figure 2: Sketch of a semiconductor-based photon counting detector's detection layout and the five main x-ray interaction mechanisms. The crystal media is enclosed between a monolithic cathode and pixelated electrodes with an electrical bias voltage across. The pixelated electrodes are fuse bonded onto an application specific integrated circuit (ASIC). The five main x-ray interaction mechanisms are 1) ideal detection, 2) charge-sharing between pixels, 3) x-ray fluorescence, 4) elastic and inelastic scattering, and 5) a dual x-ray photon detection event in the same pixel.

There are two methods for determining the energy of each incident x-ray photon: imaging mode and scanning mode [16]. The first imaging mode is a static threshold method, where the energy resolution is determined by a number of fixed comparators in the ASIC. This static method is limited in the number of channels, and usually has less than ten energy channels. The second scanning mode has a dynamic number of energy channels achieved by sweeping the threshold over an energy range. In scanning mode, the number of channels is limited by the read-out time of the detector. The reader is referred to *"Tutorial on X-ray photon counting detector characterization"* [16] for a more detailed discussion of the inner workings of PCDs.

The energy range and resolution are related to the pixel dimensions (width, length, and thickness), and the design and sensitivity of the ASIC [16]. Generally, the consequence of improving the energy resolution, thereby having more energy channels, comes at the cost of an increased read-out-time or having larger pixel dimensions. This will result in a reduced saturation level and a larger spatial resolution, respectively.

The best spectral energy resolution is obtained using a point detector with a single pixel. In order to use such detectors in XCT the detector must be translated across a 2D range of positions to generate a 2D image at each projection. 2D area detectors can image a larger area at once, ideally an entire projection, but at a worsened spectral resolution and with more detection artefacts (discussed in section 3.1.1). 1D line detectors are a compromise allowing for reasonable energy resolution while only requiring a one-dimensional translation of either the detector array or sample object.

1D and 2D detectors suffer from charge-sharing, where an incident x-ray interacting in one pixel generates a signal in the near-neighbour pixels [3, 16–18]. The possible interaction process of an x-ray with the detector media is explained in the following section. A general issue with energy dispersive detectors is the bulky electronics required. The electronics take up significantly more space than the crystals and make it challenging and in some cases unfeasible, to combine multiple detectors into a gapless array.

3.1.1 The challenges of correcting of the spectral response

The previous description assumes that every x-ray interacts and is absorbed in the detector crystal. However, as with any other material an x-ray can interact with the detector crystal in several ways and undergo a series of interaction processes. Generally, five interaction processes can be identified [3, 16], see figure 2. 1) The x-ray photon produces an electron cloud in the centre regime of a single pixel (ideal detection). 2) The electron cloud is generated near the edge of a pixel so both it and its neighbour pixel detect parts of the x-ray (charge-sharing). 3) Fluorescence in crystal media causes the generation of an electron-hole pair which can be falsely detected as an x-ray incident event. 4) The x-ray photon undergoes a scattering event, potentially into another pixel, and in the case of inelastic scattering part of the incident-photons energy is either lost or detected as a lower energy photon in the incident pixel. 5) Two x-ray photons interact with the crystal during the same detection time window causing them to be detected as a single high-energy photon with the combined energy. These processes can be considered as the detector response, and the final measured signal is a convolution of the x-ray signal from the sample and the detector response function.

It is relevant to deconvolute the measured energy signal into two parts in order to compare measurements from different detector systems and to achieve better material classification by an improved energy resolution [3, 6, 8]. Removing the detector respone can clean up the measured material attenuation curves and, thereby, make it easier to distinguish it from similar materials. Several methods exist for compensating for the detector response. The main difference between the methods is the characteristics of the x-ray source used for the analysis. The method providing the most information and the best compensation use synchrotron radiation [3, 16], other methods also exist using radioactive isotopes, x-ray fluorescence, and regular laboratory source [16]. The method should be chosen based on considerations of which of the five interaction mechanisms are relevant in the energy range of interest, more than one is likely relevant.

3.1.2 The opportunities of material classification using energy dispersive XCT data

Different data analysis pipelines are used for handling energy dispersive XCT data [4–6, 18, 20]. In general, the imaged artefact form a stack of images, where the data set acquired at each projection can be considered as a 3D stack of 2D images at each energy channel. Such a data set with N energy channels can be reconstructed N times, one for each energy channel, to produce N 3D reconstructed volumes of equal dimensions. In medical research this has been used to compare 3D reconstructed slices of a patient at different contrasts, utilising the different attenuation values, highlighting the separation between bone, tissue, and contrast agents [17, 18].

Different methods exist that are able to identify material from a measured attenuation curve [5, 8, 19, 20]. The most straightforward approach is to compare the measured attenuation curves to a list of predefined reference curves of known materials [5]. This approach relies on curve fitting and is limited by the effectiveness of the spectral correction model, the spectral resolution, and the uniqueness of the reference curve's features relative to other reference curves [5, 8]. Another method uses a reference function of the effective absorption cross-section. The function is dependent on the x-ray energy (E_k) and effective atomic number from a linear interpolation from real materials ($\sigma(Z_{eff}, E_k)$). The effective atomic number (Z_{eff}) and effective density (ρ_{eff}) can be obtained by solving a constrained minimisation scheme of the type:

$$\underset{\{Z_{eff},\rho_{eff}\}}{arg\ min} \sum_{k=i}^{N} \lambda_{E_k} \left| \widetilde{\mu}(E_k) - \rho_{eff}\ \sigma_{eff}(Z_{eff}, E_k) \right|^2 \tag{1}$$

where λ_{E_k} is a energy weight factor and $\widetilde{\mu}$ is the measured attenuation curve [5].

The solution to equation 1 provides an estimate of the effective atomic number and effective density of each voxel of the volume of interest. This is similar to what is estimated from the dual-energy decomposition algorithm for dual-energy/view scanners commonly used in aviation security. A wide selection of material decomposition methods also exists [8, 15, 17, 18, 20], where materials are decomposed, broken down into smaller parts, into some number of material reference base functions. All these methods assume that every voxel only contains a single material, which is not true for voxels near material boundaries. New methods are currently under development using machine learning and artificial intelligence to identify the appropriate material for each voxel.

4 Opportunities and challenges of implementing energy dispersive instruments

Energy dispersive detection allows for more information to be extracted from the sample, which can be used to improve the contrast [18, 20], an enhanced weighting of the photon energies [17, 18], and estimating properties used for material classification [5, 6, 17, 19, 20]. Improving the ability to separate objects with nearly similar attenuation properties will increase the accuracy of material classification [5, 8]. Since certain benign materials have attenuation curves nearly similar to some threats, the ability to better separate them will reduce the number of false classifications and thereby the number of false alarms. Reducing the number of false alarms will both improve the throughput of passengers and provide a more stress-free experience with security.

Energy dispersive XCT also offers improvements in industrial manufacturing. Energy dispersive detectors can be used as an alternative method to separate parts of multiple material components. By performing a reconstruction of only the high energy channels material parts with a high x-ray absorption, such as most metals, can be included, while parts of lighter absorbing materials, such as plastics, become almost transparent. This has already been used in medical applications to improve image quality in regions with metal prostheses [21], and similar applications can be imaged in industrial manufacturing for multi-material components.

Implementation of photon counting detectors comes with several challenges. These are discussed in the following.

4.1 Designing the detector geometry

Sweeping a 2D range of positions using a point detector is impractical for aviation security due to time constraints. Because of the restricted crystal size of most commercially available 2D detectors, a single detector module is insufficient to cover the full spatial range needed to measure luggage. Even combining multiple 2D detector modules is not enough, because the bulky electronics only allow for a limited amount of modules being combined. However, some 1D and 2D detectors have been purposely designed to operate as modules in an array of multiple detectors. 1D detectors benefit especially from the ability to be stacked on top of one another, in order to extend the effective crystal length. For aviation security applications such detector arrays can effectively be implemented in an in-line scanner system, where the luggage is translated past the detector array while data is recorded line by line, e.g. on a conveyor belt.

The throughput required for aviation security is relatively high for a CT instrument. The total acquisition time can either be spent acquiring many projections each with a short integration time (many images but poor statistics in each) or acquiring few projections with longer integration times (better statistics in each image but few images). Longer integration times are often preferred, to have sufficient statistics in each energy channel to analyse even dense regions of luggage. Again, in-line scanner designs are preferred to avoid the overhead of starting and stopping the motors. For in-line scanners, the transverse resolution (res_{trans}) of the projected image is determined by the translation speed (v_{trans}) and detector integration time (t_{int}):

$$res_{trans} = \frac{v_{trans}}{t_{int}} \tag{2}$$

To maintain a high throughput of passengers the luggage should ideally be translated continuously through the gantry. A fixed-gantry in-line system needs a full set of x-ray components: source, collimation, and detector(s), for each projection to operate, which is significantly more expensive and require a larger footprint in the instrument hall. The number of projections in a fixed-gantry system is, therefore, often limited to very few projections. The larger number of x-ray components poses a challenge for the calibration of the geometry.

4.1.1 Geometry calibration of a multi-module detector array

To produce meaningful reconstructions from a CT instrument the geometry of the source and detector components need to be well-known. It is therefore important to calibrate the geometry of an XCT scanner. From a metrology perspective, it is more challenging to calibrate the geometry of a multi-module line detector array. Muralikrishnan *et. al* [32] identified six geometry errors for a 2D detector and estimate sensitivity factors for each of the six on the sphere-to-sphere distances and sphere form errors. Similar sensitivity factors are relevant for multi-module detector arrays, besides the six geometry errors for the entire array, each individual detector will also have its own set of geometrical errors relative to the full array. The number of degrees of freedom greatly increases the complexity of the error analysis. Most current detector calibration methods do not work for fixed-gantry systems, since they rely on getting information from the same detector at each view angle (projected image) [32–34]. This is not possible in an in-line fixed-gantry design, where each detector array only contributes to a single projection. Further research is needed to establish a method for calibrating the geometry of a multi-module detector array.

4.2 Data management of energy dispersive data

From a data management perspective using energy dispersive detection greatly increase the amount of data, since every projection is recorded once for each energy channel (N times). For a detector system with e.g., 128 channels both the total file size and data to transfer get up to 128 times larger. In the setting of airport security, the total acquisition time, analyse, and for the operator to decide to raise any alarms should be less than 30 seconds. For such applications, both the hardware and software need to be extremely fast and stable in order to keep up. The communication hardware should have a gigabit transfer rate and the full reconstruction and data analysis time should ideally take less than 15 seconds. Even with modern top-of-the-line hardware equipment, this requires a complex and advanced hardware and software setup, utilising techniques from parallel computing and data management to reach the required performance. Fixed-gantry systems are well suited for such setups. The limited number of projections, due to footprint and economical limits, is here an advantage since it also reduces the amount of data significantly. The number of projections in a fixed gantry will be extremely sparse, to the point that conventional reconstruction algorithms such as the filtered-back-projection can not produce meaningful reconstructions. Instead iterative algebraic reconstruction methods should be used [2], such as Algebraic Reconstruction Technique (ART) or Simultaneous Iterative Reconstruction Technique (SIRT). The performance of iterative reconstruction algorithms has been shown to increase with the implementation of total variation reduction [10–12]. Iterative reconstruction algorithms are significantly slower than filtered-back-projection, but modern CPU and GPU parallelisation can help overcome this issue. A fixed-gantry in-line scanner design is convenient to optimise by implementing parallelisation of the acquisition, data transfer, and data analysis. For CT systems with a very sparse number of projection views, a novel reconstruction algorithm has been developed using deep learning architecture [14].

4.3 Acquiring energy dispersive data

Energy dispersive detectors have been used for research applications [5, 8] and medical scanners [17, 18]. However, access to fixed-gantry CT scanners with PCDs is limited. Acquiring data to investigate the performance of energy dispersive fixed-gantry systems and develop new calibration artefacts is challenging. Instead, a preliminary ray-tracing simulation tool has been developed for energy dispersive CT systems and validated against experimental results [2]. However, energy dispersive simulations require significantly more computational work to sample each energy channel sufficiently for statistical analysis. Modern simulation tools are currently implementing GPU parallelisation as a standard feature, which can significantly decrease the computational time for a simulation. Recently a new simulation tool for dual energy aviation security scanners has been published [13]. The novelty of the new tool is the ability to generate synthetic luggage and use the artefact through the full analysis pipeline [13]. Combining this new tool to generate synthetic luggage with fast simulation software, allows for simulations of realistic artefacts in energy dispersive fixed-gantry CT systems within an acceptable time frame.

5 Conclusion

This paper presents the benefits of improved material classification for aviation security by using energy dispersive photon counting detectors. By implementing PCDs in XCT scanners a new dimension of energy is available in the data, which allows for more information to be extracted from a scan. The current state-of-the-art energy dispersive classification techniques, as the one in equation 1, has in a research environments provide an improved material classification. Transferring these result into an aviation security environment could results in a reduced number of false alarms and fewer delays. Energy dispersive detectors also offer better contrast and material separation, which could be as beneficial for industrial manufacturing as it has been demonstrated for medical scanners [21].

The implementation of energy dispersive detection also comes with some additional challenges. Firstly, it is important to model the detector response in order to achieve both an improved spatial and spectral resolution by compensating for the x-ray interaction mechanisms as shown in figure 2. Secondly, due to the growth conditions of CdTe-based crystals, a single module of the available commercial detectors can only cover a small spatial range. Combining multiple detector modules is, therefore, necessary to cover a sufficiently large spatial large for aviation security applications. Thirdly, PCD produces a much larger amount of data, since each projection is imaged once for each energy channel. This put a large strain on the hardware and software to achieve sufficiently short acquisition and analysis time for aviation applications.

Here it is proposed to utilise an in-line CT scanner design with an array of multi-module line detectors in a fixed gantry. This makes it possible to achieve a reasonable spatial and spectral resolution with the currently available detector. A fixed-gantry design naturally has a low number of projections, which by itself would reduce the data transfer constraints and benefit greatly if implemented in a design with parallelised data acquisition, data transfer, and data analysis.

5.1 Outlook

Further research is needed before the implementation of PCDs becomes common practice. We find that one of the main remaining challenges with fixed-gantry is metrology. Specifically, the implementation of detector arrays of multiple PCD modules requires an efficient geometry calibration scheme before production maturation is reached. To achieve an efficient calibration scheme further research is required into the sensitivity factors of geometry errors. Furthermore, knowledge is needed of how to standardise spectral correction models in order to get system independent results. The development of a new simulation tool able to simulate realistic synthetic artefacts at a fast rate would greatly benefit future research as a cheaper approach to design and test the performance of energy dispersive CT systems.

Acknowledgements
This work was performed at the Danish National Facility for Imaging with X-rays (DANFIX) and supported by the Innovation Fund Denmark (grant ref. number 1044-00087B) and the company Exruptive A/S.

References

[1] Carmignato S, Dewulf W, Leach R, editors. Industrial X-ray computed tomography. Cham: Springer International Publishing; 2018.

[2] Busi M, Olsen UL, Knudsen EB, Frisvad JR, Kehres J, Dreier ES, Khalil M, Haldrup K. Simulation tools for scattering corrections in spectrally resolved x-ray computed tomography using McXtrace. Optical Engineering. 2018 Mar;57(3):037105.

[3] Dreier ES, Kehres J, Khalil M, Busi M, Gu Y, Feidenhans R, Olsen UL. Spectral correction algorithm for multispectral CdTe x-ray detectors. Optical Engineering. 2018 May;57(5):054117.

[4] Busi M, Mohan KA, Dooraghi AA, Champley KM, Martz HE, Olsen UL. Method for system-independent material characterization from spectral X-ray CT. NDT & E International. 2019 Oct 1;107:102136.

[5] Busi M, Kehres J, Khalil M, Olsen UL. Effective atomic number and electron density determination using spectral x-ray CT. InAnomaly Detection and Imaging with X-rays (ADIX) IV 2019 May 14 (Vol. 10999, pp. 7-17). SPIE.

[6] Jumanazarov D, Koo J, Busi M, Poulsen HF, Olsen UL, Iovea M. System-independent material classification through X-ray attenuation decomposition from spectral X-ray CT. NDT & E International. 2020 Dec 1;116:102336.

[7] Jumanazarov D, Koo J, Kehres J, Poulsen HF, Olsen UL, Iovea M. Material classification from sparse spectral X-ray CT using vectorial total variation based on L infinity norm. Materials Characterization. 2022 May 1;187:111864.

[8] Jumanazarov D, Koo J, Poulsen HF, Olsen UL, Iovea M. Significance of the spectral correction of photon counting detector response in material classification from spectral x-ray CT. Journal of Medical Imaging. 2022 Jun;9(3):034504.

[9] R. E. Alvarez, and A. Macovski. "Energy-selective reconstructions in x-ray computerised tomography." Physics in Medicine & Biology 21, no. 5 (1976): 733.

[10] S. Degirmenci, D.G. Politte, C. Bosch, N. Tricha, and J.A. O'Sullivan, Acceleration of iterative image reconstruction for x-ray imaging for security applications. In Computational Imaging XIII Vol. 9401 (2015), pp. 96-110. SPIE.

[11] E.Y. Sidky and X. Pan, Image reconstruction in circular cone-beam computed tomography by constrained, total-variation minimization. Physics in Medicine & Biology, 53(17) (2008), p.4777.

[12] Sidky EY, Kao CM, Pan X. Accurate image reconstruction from few-views and limited-angle data in divergent-beam CT. Journal of X-ray Science and Technology. 2006 Jan 1;14(2):119-39.

[13] Manerikar A, Li F, Kak AC. DEBISim: A simulation pipeline for dual energy CT-based baggage inspection systems. Journal of X-Ray Science and Technology. 2021 Jan 1;29(2):259-85.

[14] Han Y, Kang J, Ye JC. Deep learning reconstruction for 9-view dual energy CT baggage scanner. arXiv preprint arXiv:1801.01258. 2018 Jan 4.

[15] Eger L, Do S, Ishwar P, Karl WC, Pien H. A learning-based approach to explosives detection using multi-energy x-ray computed tomography. In2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011 May 22 (pp. 2004-2007). IEEE.

[16] Ren L, Zheng B, Liu H. Tutorial on X-ray photon counting detector characterization. Journal of X-ray science and technology. 2018 Jan 1;26(1): pp 1-28.

[17] Flohr T, Petersilka M, Henning A, Ulzheimer S, Ferda J, Schmidt B. Photon-counting CT review. Physica Medica. 2020 Nov 1;79: pp 126-36.

[18] Danielsson M, Persson M, Sjölin M. Photon-counting x-ray detectors for CT. Physics in Medicine & Biology. 2021 Jan 28;66(3):03TR01.

[19] Shikhaliev PM, Xu T, Molloi S. Photon counting computed tomography: concept and initial results. Medical physics. 2005 Feb;32(2): pp 427-36.

[20] Wang X, Meier D, Taguchi K, Wagenaar DJ, Patt BE, Frey EC. Material separation in x-ray CT with energy resolved photon-counting detectors. Medical physics. 2011 Mar;38(3): pp 1534-46.

[21] Leng S, Bruesewitz M, Tao S, Rajendran K, Halaweish AF, Campeau NG, Fletcher JG, McCollough CH. Photon-counting detector CT: system design and clinical applications of an emerging technology. Radiographics. 2019 May;39(3): pp 729.

[22] Rajendran K, Petersilka M, Henning A, Shanblatt ER, Schmidt B, Flohr TG, Ferrero A, Baffour F, Diehn FE, Yu L, Rajiah P. First clinical photon-counting-detector CT system: Technical evaluation. Radiology. 2022 Apr;303(1): pp 130.

[23] Scholze F, Procop M. Modelling the response function of energy dispersive X-ray spectrometers with silicon detectors. X-Ray Spectrometry: An International Journal. 2009 Jul;38(4): pp 312-21.

[24] Dinapoli R, Bergamaschi A, Henrich B, Horisberger R, Johnson I, Mozzanica A, Schmid E, Schmitt B, Schreiber A, Shi X, Theidel G. EIGER: Next generation single photon counting detector for X-ray applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2011 Sep 11;650(1): pp 79-83.

[25] Kraft P, Bergamaschi A, Broennimann C, Dinapoli R, Eikenberry EF, Henrich B, Johnson I, Mozzanica A, Schlepütz CM, Willmott PR, Schmitt B. Performance of single-photon-counting PILATUS detector modules. Journal of synchrotron radiation. 2009 May 1;16(3): pp 368-75.

[26] Shikhaliev PM, Fritz SG, Chapman JW. Photon counting multienergy x-ray imaging: Effect of the characteristic x rays on detector performance. Medical physics. 2009 Nov;36(11): pp 5107-19.

[27] D. Vukadinovic and D. Anderson, X-ray Baggage Screening and Artificial Intelligence (AI), EUR 31123 EN, Publications Office of the European Union, Luxembourg (2022), ISBN 978-92-76-53494-5, doi:10.2760/46363, JRC129088

[28] Regulation (EC) No 300/2008 of the European Parliament and of the Council of 11 March 2008 on common rules in the field of civil aviation security and repealing Regulation (EC) No 2320/2002 (Text with EEA relevance)

[29] Commission Implementing Regulation (EU) 2015/1998 of 5 November 2015 laying down detailed measures for the implementation of the common basic standards on aviation security (Text with EEA relevance)

[30] Congress.gov. "S.1447 - 107th Congress (2001-2002): Aviation and Transportation Security Act." November 19, 2001, http://www.congress.gov/., 2001 (Accessed 27 June 2022)

[31] Aeronautics Act, R.S.C. 1985, c. A-2, https://laws-lois.justice.gc.ca/eng/acts/a-2/, 1985 (Accessed 27 June 2022)

[32] Muralikrishnan B, Shilling M, Phillips S, Ren W, Lee V, Kim F. X-ray computed tomography instrument performance evaluation, Part I: Sensitivity to detector geometry errors. Journal of Research of the National Institute of Standards and Technology. 2019;124:1.

[33] Li G, Luo S, You C, Getzin M, Zheng L, Wang G, Gu N. A novel calibration method incorporating nonlinear optimization and ball-bearing markers for cone-beam CT with a parameterized trajectory. Medical physics. 2019 Jan;46(1):152-64.

[34] Panetta D, Belcari N, Del Guerra A, Moehrs S. An optimization-based method for geometrical calibration in cone-beam CT without dedicated phantoms. Physics in Medicine Biology. 2008 Jun 26;53(14):3841.