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Efficient material decomposition method for dual-energy X-ray cargo inspection system

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ABSTRACT

Dual-energy X-ray inspection systems are widely used today for it provides X-ray attenuation contrast of the imaged object and also its material information. Material decomposition capability allows a higher detection sensitivity of potential targets including purposely loaded impurities in agricultural product inspections and threats in security scans for example. Dual-energy X-ray transmission data can be transformed into two basis material thickness data, and its transformation accuracy heavily relies on a calibration of material decomposition process. The calibration process in general can be laborious and time consuming. Moreover, a conventional calibration method is often challenged by the nonuniform spectral characteristics of the X-ray beam in the entire field-of-view (FOV). In this work, we developed an efficient material decomposition calibration process for a linear accelerator (LINAC) based high-energy X-ray cargo inspection system. We also proposed a multi-spot calibration method to improve the decomposition performance throughout the entire FOV. Experimental validation of the proposed method has been demonstrated by use of a cargo inspection system that supports 6 MV and 9 MV dual-energy imaging.

1. Introduction

Cargo inspection systems (CISs) play an important role in detecting anomalies such as purposely loaded impurities in agricultural products, smuggling goods, and threats [1]. Among various inspection technologies, dual-energy X-ray system can provide not only X-ray attenuation contrast of the imaged object but also its material information thus enhancing the detection capability [2–4]. X-ray imaging that uses nonlinear dependence of the attenuation of the materials on X-ray energy spectrum has been actively investigated and utilized. In medical applications, for example, nonlinear dependence of the attenuation dominantly through photoelectric interaction and Compton scattering has been used for correction of the image artifacts related to scatter [5] and beam hardening [6–9].

Material differentiation using dual energy X-ray spectra is one of the key applications of such nonlinear dependence of the attenuation. Since the first demonstration of material decomposition capability of dual-energy X-ray imaging by R. E. Alvarez and A. Macovski [10], it has been actively applied to radiography and computed tomography. The material decomposition methods can be roughly classified into two categories one of which uses the ratio of the attenuation coefficients at two different spectra directly and the other uses basis-material-based decomposition. The basis-material decomposition methods can be further divided into one that uses X-ray spectrum estimation together with the database of material attenuation [11–13] and the other that uses the calibration phantoms consisting of two basis materials [6,14–16]. Stemming from the dual-energy X-ray imaging physics, spectral imaging techniques have been promoted through advanced imaging system capabilities [17–22].

For most commercially available CISs, material decomposition based on the ratio of the attenuation coefficients at two different spectra is in active use. By use of the look-up table established through a systematic and laborious data acquisition procedure, one can decompose dual-energy images into a material map [3,4]. A given material is scanned at various thicknesses by dual-energy X-ray scanner, and the ratio of the logarithmic transparencies acquired at two different X-ray spectra is plotted against the thickness of the given material. Such plots are

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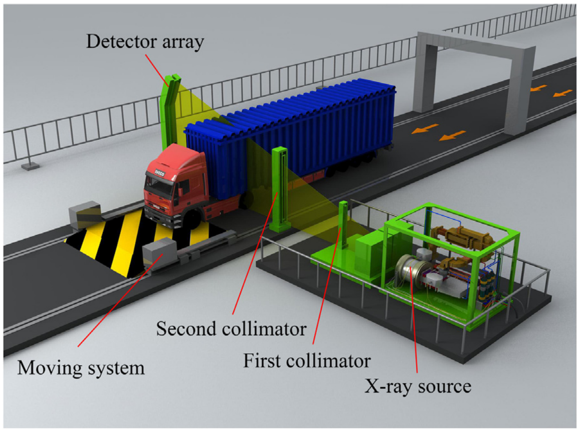

Fig. 1. Illustration of a container inspection system.

acquired similarly from other materials. It is assumed that the range of the ratio of the logarithmic transparencies is substantially different from materials to materials in the dual-energy settings of the CIS. Therefore, as long as the ratio of the logarithmic transparencies does not overlap each other, more than two basis materials can be used for material decomposition. Practically, four-material decomposition is available in conventional CISs. One of the caveats of this approach is that the accuracy of the thickness retrieval of a material is challenged when the thickness increases since the associated ratio of the logarithmic transparencies does not change substantially along the thickness. The chance of an overlap between the ratios of the logarithmic transparencies of two different materials, such as acrylic and aluminum, would also increase as the thickness of a material is significantly large.

We propose an efficient calibration method in this work for dual-energy material decomposition in CISs. The proposed method can improve the accuracy of material discrimination by utilizing a polynomial decomposition model to fully reflect the characteristics of polychromatic X-ray interaction. Moreover, this method can incorporate physical factor effects such as beam hardening and scatter through the calibration process that is based on tomographic image reconstruction of a known calibration phantom. The calibration phantom is relatively simple and handy compared to the ones used in the transparency ratio method, and the associated calibration process can be performed with much less effort and time.

As will be discussed in the following sections, X-ray energy spectrum has a dependence on the beam direction [23–25]. As the dual-energy material decomposition largely depends on the spectral properties of the X-ray beam, the material decomposition method that is optimized at a given beam direction may produce suboptimal decomposition at other beam angles. Additionally, nonuniform detector responses in conjunction with the X-ray beam spectra may contribute to the suboptimal decomposition. Since the proposed calibration method is fast and efficient, multiple calibrations at various beam angles can be performed. We conducted three-spot calibration covering the field-of-view (FOV) in this work, and show that an improved performance of the material decomposition is achievable throughout the entire FOV. The experiments were carried out on a 6 MeV/9 MeV dual-energy CIS developed by Korea Atomic Energy Research Institute (KAERI).

2. Methods and materials

2.1. Proposed calibration method

The proposed material decomposition method has been largely inspired by Stenner's empirical calibration method that was developed for medical dual-energy CT imaging system [6]. The underlying assumption is that a material-selective projection can be represented by a polynomial combination of the dual-energy projections. Let q_H and q_L depict the log-transformed projections acquired at high and low X-ray energy spectra, respectively. The material-selective projection is then defined by

$$\begin{aligned} p_i &= \sum_{k=0}^{K-1}\sum_{l=0}^{L-1} c_i(k,l) q_H^k q_L^l = \sum_{k=0}^{K-1}\sum_{l=0}^{L-1} c_i(k,l) b_{k,l}(q_H, q_L) \\ &= \mathbf{c}_i \cdot \mathbf{b}(\mathbf{q_H}, \mathbf{q_L}), \end{aligned} \tag{1}$$

where $\mathbf{c}_i$ represents the material-specific decomposition coefficients to be determined through a calibration process. The index i represents the basis materials. Two basis materials are usually selected to represent low- and high-density objects, or organic and inorganic materials. In this work, we used acrylic and steel for basis materials. The polynomials $b_{k,l}(q_H, q_L) = q_H^k q_L^l$ are used as basis functions with $k = 0, \ldots, K$ and $l = 0, \ldots, L$.

Since the filtered-backprojection (FBP) algorithm for CT image reconstruction is a linear operation, the set of material-decomposition coefficients that were used for preparing material-selective projections would yield the material decomposed CT images after image reconstruction [26]. In other words, one can determine the coefficients such that the reconstructed image solely represents a single material image out of two. Acrylic-only image, or steel-only image, would be produced after image reconstruction if the coefficients were properly calibrated for acrylic, or steel, decomposition, respectively. However, two questions have to be answered if CT imaging-based material decomposition is to be used in CIS. First, does a cargo inspection system support a CT imaging? Second, does a calibration phantom guarantee a wide variety of thickness combinations of the basis materials? We have developed an object rotation system and a phantom to provide solutions to both questions.

Fig. 1 shows a schematic illustration of a CIS that includes a high-energy X-ray LINAC, beam collimators, a linear array of detectors, and a cargo translation system. 9 MV and 6 MV beams are alternatingly irradiated while the cargo is under a linear motion, producing interlaced high-/low-energy X-ray projections. As shown in Fig. 2, we made and placed an object rotating system between the beam collimators. The object rotating system can adjust the rotation center position such that the calibration can be conducted at various positions in the FOV. By rotating an object during a typical cargo inspection scan, one can acquire projection data of the scanned object in a fan-beam mode with more than 360° scan angle. Therefore, 2D CT image reconstruction can be conducted from the acquired fan-beam projection data, or often-called sinograms. The calibration phantom consists of two disks made of acrylic and steel, respectively. We would like to note that the basis materials can be chosen up to the users' preferences and the target cargos' specifications. In this paper, the focus was on demonstrating that an efficient and fast calibration is possible by use of the proposed method. Exploring the material decomposition in terms of varying basis materials would be definitely an important topic of research. We assumed a cargo composed of mostly agricultural products and metallic objects in this work. Acrylic and steel represent organic materials and metallic materials respectively. The diameters of the disks have been determined to represent possible total thickness of the scanned cargo in practice: diameters of the steel disk and of the acrylic disk 12 and 45 cm, respectively in this work. Additionally, the minimum transmission thickness of each material has also been taken into account when determining the disk diameter. The acrylic phantom is centered about the rotation axis and the steel phantom is placed in close contact with the acrylic phantom as shown in Fig. 2. This arrangement of the disks would yield a variety of thickness combinations of the two basis materials during a CT scan. On the opposite side of the steel phantom, we added a weight balance in consideration of mechanical stability. The weight balance is, however, attached outside the fan-beam so that the imaging FOV is free of the weight balance object.

Fig. 3 shows the sinograms, i.e., log-transformed projections of the calibration phantom with respect to the rotation angle over 360°, at (a)