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Research Paper

Scattering correction using continuously thickness-adapted kernels

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ABSTRACT

Quantitative reconstruction values are often miscalculated in Cone Beam Computed Tomography (CBCT) due to the presence of secondary radiation originating from scattering of photons inside the object and detector under consideration. The effect becomes more prominent and challenging in case of X-ray source of high energy (over a few 100 keV) which is used in industrial Non-Destructive Testing (NDT), due to higher scatter to primary ratio (SPR). This paper describes a scatter correction algorithm for correcting the combined scattering due to the object and the detector based on variations in Scatter Kernel Superposition (SKS) method. Scatter correction is performed for homogeneous and heterogeneous objects in a robust iterative manner suitable for high SPR, using pencil beam kernels which are simulated in computed tomography (CT) module of the CIVA software for NDT simulations. Two methods for scatter correction using SKS approach are discussed and compared in the paper. In the first method, we use a discrete approach in which kernels for only few thicknesses are used. In the second method a continuous approach is proposed where the kernels are analytically parameterised for all thicknesses. The results obtained after scatter correction are well within the expected reconstruction values. The continuous method produces better edge enhanced corrected projections and the method results in improved reconstruction values than the discrete method.

1. Introduction

Compared to highly collimated fan beam computed tomography (CT), cone-beam computed tomography (CBCT) is based on 2D detectors of larger area, which makes CBCT bear a high level of X-ray scatter. Inadequate modeling of this scatter leads to cupping and streaking artifacts [1] and to a global degradation of image quality in CBCT.

There are various existing CBCT scatter correction methods which can be summed up mainly into two categories: pre-processing methods, and post-processing methods. Pre-processing methods modify the X-ray system and are able to separate the scatter from the primary photons based on the difference of their incidence angles, but require a higher dose. These include anti-scatter grids method (which make use of highly attenuating grids which are mounted directly on the top of the detector) [2] and the airgap method [3]. The post-processing methods estimate the scatter signal from the scatter-contaminated projection using some prior knowledge of the scatter distribution. These include measurement based methods such as beam stop array [4,5] where a high atomic number material like lead (strip or a disc) is inserted between the X-ray source and the imaged object. Such methods cause increased X-ray exposure due to more than one scans per projection, prolong the scanning time and are also subject to error due to object motion. Many other software based post-processing have been proposed for scatter estimation and correction [6,7].

In this paper we propose to focus on Scatter Kernel Superposition (SKS) method [8–11] in which the scatter signal is modeled as the sum of the scatter contributions from a group of pencil beams passing through the object. It approximates the scatter distribution, as the convolution of primary signal with scatter kernels. This method requires no additional hardware, scanning time and additional dose. Pencil beam kernels are thickness dependent kernels and there is an appreciable change in the amplitude and shape of these kernels with respect to small variation in the thickness of the object. The scatter correction methods are based on a discrete set of thickness-dependent kernels and for a range of thickness only one kernel is used. This method gives satisfactory results in many applications. However, when a high range is considered (typically [300,500] keV), the SPR is expected to be very large and the different steps of the SKS correction algorithm have to be reconsidered. In particular a better sampling of the kernels with respect to the thickness of the object is required to get an accurate model of variability in shape and in amplitude of the scatter kernels over the whole thickness range. When the scatter level is not negligible with respect to the primary radiations, the robustness and the convergence of the

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iterative correction scheme become critical since a slight overestimation of the scatter radiation level might lead to large negative values of the primary transmittance.

We propose in this paper a twofold modification of Sun and Starlack [11] SKS approach to tackle X-ray imaging with larger SPR: an analytical parameterization of the scatter kernel is derived in terms of material thickness and a multiplicative iteration approach is implemented. We begin by describing the methodology of scatter correction with pencil beam kernels. This is followed by the description of generation of kernels and development of the analytic expression for continuous kernel map. The modeling of the kernels for heterogeneous object is described in detail. We then describe the iterative scheme followed for the scatter correction. Afterwards the acquisition set up and objects used are described in detail. Finally the results obtained after the reconstruction performed using FDK algorithm are compared for discrete set of kernels and continuous map of kernels for homogeneous and heterogeneous object.

2. Method and materials

2.1. Scatter correction using pencil beam kernels

The measured signal at the detector $I(m,n)$ has two components: $P(m,n)$ is the primary signal contributed by the photons passing directly without any attenuation or scattering and $S(m,n)$ is the signal contribution of the scattered photons from the object and the detector. Therefore, the measured signal is given by:

$$I(m,n) = P(m,n) + S(m,n) \tag{1}$$

where m and n correspond to the pixel position on the detector.

The scatter signal can be modeled as the sum of the scatter contributions from a group of pencil beams passing through the object and the detector. For each pencil beam input, a resulting kernel which has the weight of the scatter to primary ratio is determined. The total scatter signal $S(m,n)$ can then be modeled as:

$$S(m,n) = \sum_k \sum_l P(k,l) h_{T(k,l)}(m-k, n-l) \tag{2}$$

where, h_T is the thickness (T) dependent kernel, with amplitude equal to the ratio of the scattered signal at the current pixel to the primary signal, at the pencil beam centered pixel. The thickness is calculated with the Beer Lambert law

$$T(k,l) \approx \frac{1}{\mu} \ln \frac{O(k,l)}{P(k,l)} \tag{3}$$

with μ being the attenuation constant of the object under consideration at the mean energy of the spectrum used. The pencil beam kernel h_T can be fitted into the equation formed by an amplitude factor $C(k,l)$ (which is a function of the primary signal $P(m,n)$ and the un-attenuated air intensity $O(m,n)$) and a form-function $G(m-k, n-l)$ consisting of two circularly symmetric Gaussian functions describing the shape of the kernel:

$$h_T(m-k, n-l) = C(k,l) G(m-k, n-l) \tag{4}$$

$$C(k,l) = \left(\frac{P(k,l)}{O(k,l)}\right)^{\alpha} \ln\left(\frac{O(k,l)}{P(k,l)}\right)^{\beta} \tag{5}$$

$$G(m-k, n-l) = A \exp\left(-\frac{(m-k)^2 + (n-l)^2}{2\sigma_1^2}\right) + B \exp\left(-\frac{(m-k)^2 + (n-l)^2}{2\sigma_2^2}\right) \tag{6}$$

Eq. (2) then becomes

$$S(m,n) = \sum_k \sum_l P(k,l) C(k,l) G(m-k, n-l) \tag{7}$$

In the discrete kernel approach, a few thickness ranges are selected from zero to maximum thickness of the object and a single average value for fitting parameters $\alpha, \beta, A, B, \sigma_1, \sigma_2$ is obtained for one particular thickness range. The superposition convolution equation is thus modified to the form

$$S(m,n) = \sum_i \sum_k \sum_l P(k,l) R_i(k,l) C_i(k,l) G_i(m-k)(n-l) \tag{8}$$

$$R_i(k,l) = \begin{cases} 1, & \text{if } T_i(k,l) \le T(k,l) < T_{i+1}(k,l) \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where i gives the number of thickness groups and T_i and T_{i+1} are the lower and upper bound thicknesses of the ith group.

In the continuous approach, the fitting parameters are also interpolated with respect to the thicknesses to form a continuously varying profile of kernels. Hence Eq. (8) is modified to:

$$S(m,n) = \sum_k \sum_l P(k,l) C(k,l,T(k,l)) G(m-k, n-l, T(k,l)) \tag{10}$$

2.2. Generation and fitting of kernels

Monte Carlo (MC) simulations were performed in the CT module of CIVA software [12] for the generation of kernels. Developed by CEA LIST, CT module of CIVA combines deterministic and MC approach for the generation of primary and secondary radiation in tomography [13].

For the simulation of the kernels, imaging geometry corresponding to the acquisition set up was modeled in CIVA. Pencil beam source was impinged on slabs of same material as the object under study and discrete set of point spread 2D kernels were obtained on the flat panel detector. Eq. (4) was fit on these kernels

Fig. 1. Picture of sample of the iron hub [5].

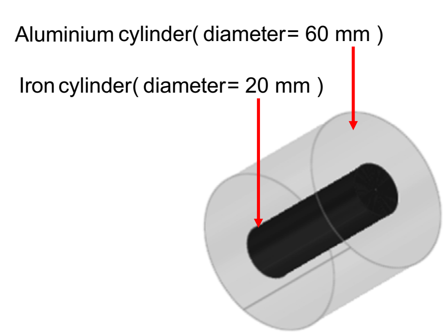

Fig. 2. Set-up of heterogeneous object consisting of a 60 mm diameter cylinder of aluminum containing a 20 mm diameter cylinder of iron.