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Improvement of radiographic visibility using an image restoration method based on a simple radiographic scattering model for x-ray nondestructive testing

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ABSTRACT

In conventional radiography, image visibility is often limited mainly due to the superimposition of the object's structure under investigation and scattered x-rays. Several methods, including the antiscatter grid technique, the air-gap technique, and scatter correction methods using measurements, mathematical-physical modeling, or a combination of both, have been extensively investigated in an attempt to overcome these difficulties. However, these methods require special equipment, geometry, and extra work to measure the scatter characteristics. In this study, we propose a new image restoration method based on a simple radiographic scattering model in which the intensity of the scattered x-rays and the direct transmission function of a given object are estimated from a single x-ray image by using the dark-channel prior. We implemented the proposed algorithm and performed a systematic experiment by using a 450-kV industrial x-ray inspection system to demonstrate its viability for nondestructive testing. Our results indicated that the structure of the examined object was much more clearly visible in the restored image, considerably improving the radiographic visibility.

1. Introduction

Radiographic testing is commonly used in the field of nondestructive testing (NDT) for the inspection of industrial parts, material characterization, and the security check and examination of various specimens [1–3]. In the welding industry, especially, radiographic testing is essential to ensure that the weld quality meets the design and safety and reliability requirements. Recently, we established a high-energy x-ray inspection system to examine large and dense industrial objects. However, in conventional radiography, image visibility is often limited mainly due to the superimposition of the object's structure and scattered x-rays. Several scatter reduction methods, including the antiscatter grid and air-gap techniques, and scatter correction methods using measurements (*e.g.*, beam-stop measurement behind the object of interest to characterize the scatter kernel), mathematical-physical modeling (analytical and Monte-Carlo models), or a combination of both, have been extensively investigated in attempt to overcome these difficulties [4–9]. However, these methods demand special equipment, geometry, and extra work to measure the scatter characteristics. In addition, methods that may be useful in one application may not work in another. For example, antiscatter grids are considered indispensable tools in clinics to improve image contrast; but they are useless for high-energy x-ray inspection systems due to the high transmission of scattered x-rays [10].

In this study, we propose a new image restoration method based on a simple radiographic scattering model in which the intensity of the scattered x-rays and the direct transmission function of a given object are estimated from a single x-ray image. We implemented the proposed algorithm and performed an experiment by using a 450-kV industrial x-ray inspection system to demonstrate its viability for NDT. In the following sections, we briefly describe the proposed image restoration scheme and present the results.

2. Materials and methods

Fig. 1 shows the schematic illustration of a simple radiographic scattering model for radiography image restoration. In conventional radiography, the observation of an object on the detector, $I(x,y)$, can be

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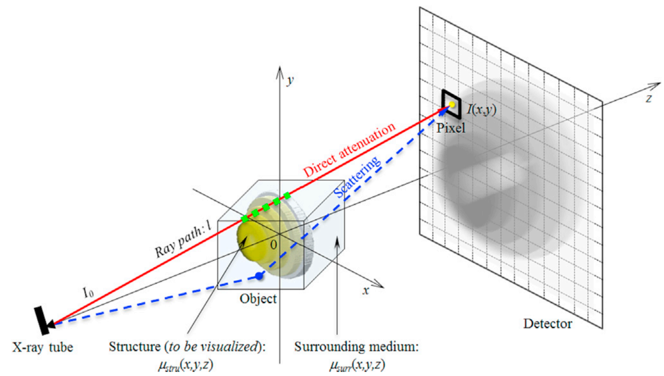

Fig. 1. The schematic illustration of a simple radiographic scattering model for radiography image restoration. Here, $I(x,y)$ is the observation of an object on the detector, μ_{stru} and μ_{surr} are the linear attenuation coefficients of the structure and the surrounding medium, respectively, and l is the ray path of the object.

simply described by Eq. (1) in a way similar to that used in the Koschmieder model [11]:

$$I(x,y) = t \cdot J(x,y) + (1-t) \cdot A,$$
$$t(x,y) = exp\left(-\int_l \mu_{surr}(x,y,z)dl\right), \tag{1}$$
$$J(x,y) = I_0 exp\left(-\int_l \mu_{stru}(x,y,z)dl\right),$$

where $t(x,y)$ describes the direct transmission function of a given medium surrounding the structure, $J(x,y)$ is the intrinsic image intensity (*i.e.*, grayscale) of the structure, A is the global image intensity of the scattered x-rays, $\mu_{surr}(x,y,z)$ and $\mu_{stru}(x,y,z)$ are the linear attenuation coefficients of the surrounding medium and the structure, respectively, and l is the path length of the object. In this model, as described in Eq. (1), the intrinsic observation of the structure is deteriorated due to the superimposition caused by the direct transmission of the surrounding medium and the artifacts caused by scattered x-rays and noise. If deteriorated images in radiography are to be recovered, the radiographic scattering model requires the image intensity of the scattered x-rays A and the transmission function $t(x,y)$ to be estimated. Once A and $t(x,y)$ are properly estimated, $J(x,y)$ can be restored by using

$$J(x,y) = \frac{I(x,y) - (1 - t(x,y)) \cdot A}{t(x,y)}. \tag{2}$$

However, the proposed scheme has the minimal requirement for a single x-ray image, which is highly under constrained. Thus, more constraints on the unknowns should be exploited. Meng et al. proposed an efficient image dehazing method with a boundary constraint and contextual regularization in computer vision, which requires only a few general assumptions [12]. Dehazing is an image restoration technique extensively studied in computer vision to recover hazy (or *foggy*) images that are often caused by suspended atmospheric particles such as haze, fog, smoke, and mist [13–16]. The goal of dehazing is to improve the contrast of hazy images and restore the visibility of imaging scenes. Thus, applying the dehazing technique to radiography could be helpful in improving image visibility.

In the proposed scheme, $J(x,y)$ is restored from $I(x,y)$ based on Eq. (2) with two unknowns, A and $t(x,y)$, which necessitates a solution of an ill-posed inverse problem. Recently, He et al. proposed a novel prior, the so-called *dark-channel prior* (DCP), to eliminate the difficulty of the inverse problem [17]. The DCP is derived from the characteristic of natural outdoor images in which the intensity of at least one-color channel within a local patch is close to zero. If $I(x,y)$ is a grayscale image, the DCP is mainly used to describe the plausible minimum values in an image patch (a patch size of 21×21 was used in this study) [18]. Note that A is described as a global value of the scattering in the optical atmospheric scattering model and is effectively estimated using the DCP. In this study, we adopted this constraint in the radiographic scattering model and obtained the value of A by using minimum filtering and selecting the maximum value from the filtered image. The minimum filtering method uses a nonlinear spatial filter whose response is based on minimum ordering (ranking) the pixels contained in the image area encompasses by the filter, and then replacing the value of the center pixel with the value determined by the ranking result.

The optimal transmission function, t^*, can normally be found by minimizing the following objective function φ in the weighted l^1-norm based contextual-regularization framework, as described by

$$t^* = \arg\min_{t^{(k)} \in w} \varphi\left(t^{(k)}\right),$$
$$\varphi\left(t^{(k)}\right) = \frac{\lambda}{2}\left\|t^{(k)} - t_b\right\|_2^2 + \left\|W \circ \left(D \otimes t^{(k)}\right)\right\|_1, \tag{3}$$
$$W = exp\left(-\frac{\|I(x) - I(y)\|^2}{2\sigma^2}\right),$$

where w is the set of feasible $t^{(k)}$, $\frac{\lambda}{2}\left\|t^{(k)} - t_b\right\|_2^2$ is the fidelity term, which measures the difference between $t^{(k)}$ and an appropriate boundary

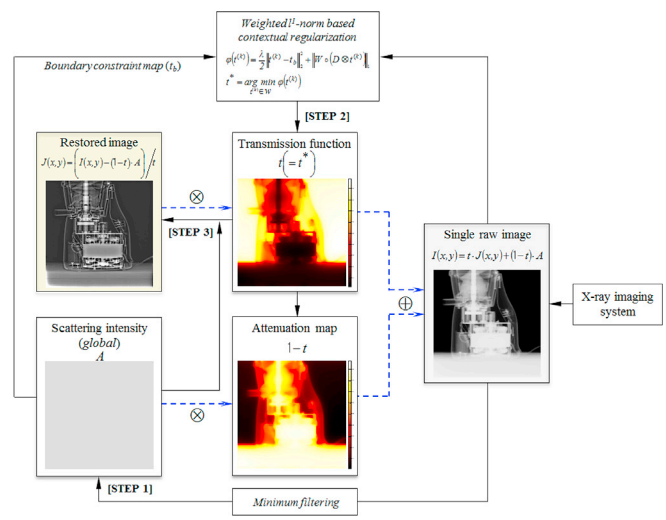

Fig. 2. A simplified flowchart of the proposed image restoration process based on a simple radiographic scattering model.

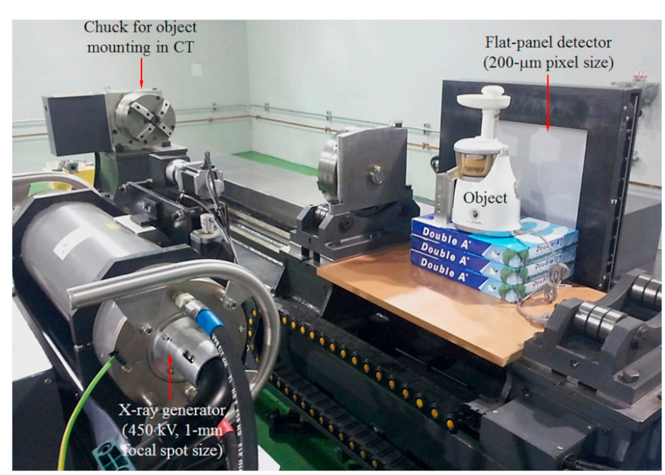

Fig. 3. The high-energy x-ray inspection system established for NDT which consisted of an industrial x-ray generator (tube voltage: 450 kV, focal spot size: 1 mm) and a CCD flat-panel detector (pixel resolution: 200 μm, pixel matrix: 2048×2048).

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