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High-resolution coded-aperture design for compressive X-ray tomography using low resolution detectors[☆]

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ABSTRACT

One of the main challenges in Computed Tomography (CT) is obtaining accurate reconstructions of the imaged object while keeping a low radiation dose in the acquisition process. In order to solve this problem, several researchers have proposed the use of compressed sensing for reducing the amount of measurements required to perform CT. This paper tackles the problem of designing high-resolution coded apertures for compressed sensing computed tomography. In contrast to previous approaches, we aim at designing apertures to be used with low-resolution detectors in order to achieve super-resolution. The proposed method iteratively improves random coded apertures using a gradient descent algorithm subject to constraints in the coherence and homogeneity of the compressive sensing matrix induced by the coded aperture. Experiments with different test sets show consistent results for different transmittances, number of shots and super-resolution factors.

1. Introduction

Computed tomography (CT) is a technique used to generate images of the internal structure of 3D objects [1]. It plays an important role in different applications such as industrial quality control [2], security [3], forensic sciences [4], and medical diagnosis [5]. A CT scanner consists of an array of detectors on the opposite side of an X-ray source. The images are produced when the X-ray beams are attenuated through the object and recorded by the set of detectors, while these elements rotate around the object at different projection angles. The image of the object is then generated by means of different reconstruction algorithms. Specifically, the reconstruction problem can be interpreted as solving an overdetermined linear system in which a large number of measurements is required in order to generate a suitable reconstruction [6].

Recently, different configurations of the source and detectors have been studied in order to improve CT imaging in terms of radiation dose, image quality, or acquisition time. Regarding the radiation, it is desirable to reduce its dose which, in turn, is directly related with the number of measurements and the exposure time. As for the image quality, a lot of efforts have been devoted in order to improve the spatial resolution and signal-to-noise ratio (SNR) of the reconstructed image. These problems have been tackled either by increasing the number of pixels by unit area, at the cost of a lower SNR due to the reduced pixel size [7], or by using a bigger detector size in order to decrease noise, at the expense of spatial resolution and higher acquisition times [8]. Alternatively, compressive sensing (CS) has been investigated more recently for improving image quality by means of image processing.

The motivation behind Compressive Sensing Computed Tomography (CS CT) is reducing the number of measurements at the cost of temporal resolution [9]. Specifically, CS CT assumes that full-resolution is achievable from a reduced number of measurements, given that the image has a sparse representation in some transform domain. In traditional CT, an image is reconstructed using a full measurement set of densely sampled projections. In contrast, CS CT is used to recover the original underlying signal from the reduced set of measurements. In order to reduce the number of measurements, a physical element between the source and the object, namely the *coded aperture*, is used. As illustrated in Fig. 1(a), the aim of the coded aperture is blocking some of the X-rays before they reach the object [10]. In this case, the size of the blocking aperture is designed with the same size of a single detector. The blocking of some X-rays has the advantage of reducing not only the amount of measurements required but also the exposure of the object to radiation.

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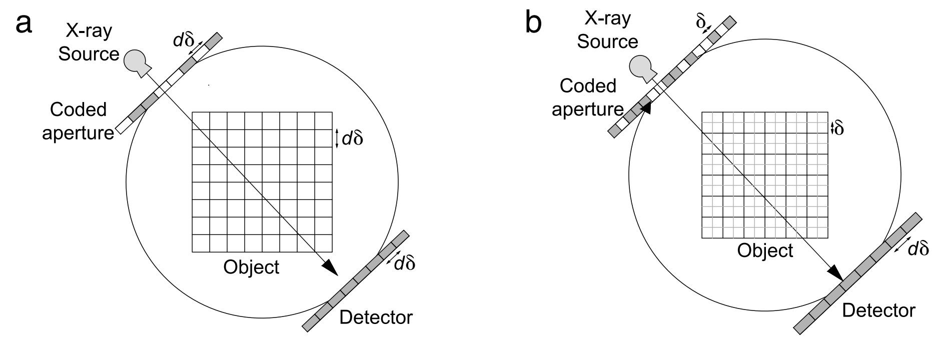

Fig. 1. Compressive sensing computer tomography. (a) Classical architecture based on CS using a coded aperture with size $d\delta$. (b) Proposed architecture with coded aperture elements of size δ for a super-resolution factor of d.

Previous efforts in CS CT have focused on either solving computational issues that arise in the formulation of CS for CT, or studying different sampling schemes. On the one hand, in classical CT, the generated tomography image is obtained using different reconstruction algorithms, such as the Filtered back projection and the Algebraic Reconstruction technique [1,6]. However, when the number of measurements is reduced, as is the case of CS, the system will become highly under-determined and unstable. In this case, methods based on total variation have demonstrated their usefulness for CS CT [11,12]. On the other hand, the sampling scheme can be modified by changing the location and distribution of the blocking elements in the coded aperture or by removing some angles during the acquisition of the CT sequence [13,14]. The random sampling scheme used in CS impacts the reconstruction process since it leads to different projection sets.

The difference in the distribution of elements between the rows or columns in the bi-dimensional coded aperture is known as the *variability*. In the design of coded apertures, it is desirable to attain high variability thus limiting the linear dependency of random measurements, also known as *incoherence* [15]. The study of coded apertures has shown that it is possible to find better distributions than pure random sampling [10]. Typically, a random scheme is appropriate to reduce the required quantity of information. However, Brady et al. [9] show that a designed coded aperture can exploit characteristics as the diffraction produced by the X-ray signals.

In this work, we propose to increase the resolution of the reconstructed image in a CS CT system with a low resolution detector by means of high-resolution coded apertures. Our approach, as illustrated in Fig. 1(b), allows the use of low-resolution detectors with d times the size δ of a single coded aperture. In contrast to previous research, in which the size of the coded aperture coincides with the size of the detector, the proposed approach will allow to recover high-resolution images from low-resolution detectors thus achieving super-resolution (SR). Our hypothesis is that apertures with reduced size can be used to encode high-resolution information in low-resolution detectors by using multiple projections of the X-ray beam. For this purpose, multiple shots are captured for each projection in the acquisition process. The challenge is the design of a sampling scheme in order to improve the reconstruction result by reducing the coherence in the coded aperture matrix and increasing the variability of the blockages. Specifically, the improvement of the coded apertures is found through a gradient descent of the Frobenius norm formulated to obtain a minimal value in the covariance of the sensing system matrix, subject to constraints of homogeneity in the measurements for a fan beam CT architecture.

Simulations results show that, with the proposed approach, it is possible to reconstruct high-resolution images from low-resolution detectors, thus showing that super-resolution is achievable in CT. This is accomplished by acquiring multiple shots with high-resolution coded apertures and reconstructing the image using CS theory. In addition, coded apertures designed using the proposed method show improvements of up to 3 dB with respect to purely random apertures.

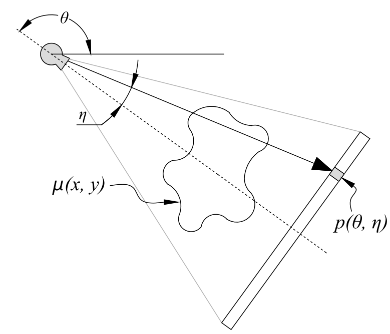

Fig. 2. CT architecture. The measured projection $P(\theta, \eta)$ is a function of the angle of projection θ and the direction of each X-ray η. The aim is to recover the continuous linear attenuation coefficient $\mu(x, y)$.

2. Background

In CT, the aim is to recover the linear coefficient $\mu(x, y)$ that characterizes the attenuation properties of an object as a function of its spatial coordinates x and y. The projection measurement at the detector $P(\theta, \eta)$ is a function of the X-ray direction η and the angle of the projection θ:

$$P(\theta, \eta) = \int E(\theta, \eta) \exp\left(-\int_L \mu(x, y) dl\right) dE \tag{1}$$

where the integral in the exponential is taken along the path of the X-ray L and $E(\theta, \eta)$ accounts for both the directional and spectral response of the detector to the source beam energy (see Fig. 2).

Notice that, in general, CT is aimed at recovering a 3-dimensional attenuation field μ. However, for the sake of clarity, the 2-dimensional case is considered in (1). The extension to 3D is straightforward by applying this process to each slice of the 3D volume. This convention is kept in the remaining of this paper. Below, we introduce the mathematical discrete model for compressed sensing computed tomography with high resolution apertures (Section 2.1) and we formulate the problem for coded aperture optimization (Section 2.2). A summary of the symbols and notation used in this paper can be found in Table 1.

2.1. Compressed sensing computed tomography

The acquisition process in (1) can be discretized as follows: let $\mathbf{p}$ be the vectorized set of M measurements on the detector for all projection angles and ray directions, such that $\mathbf{p} \in \mathbb{R}^M$. The total number of measurements is the result of the product $M = \gamma \times \omega$, where γ is the number of detectors in the sensor, and ω the number of angular projections of the acquisition. The aim is to recover the set of N attenuation coefficients f_i for $i = 1, 2, \ldots, N$, which in vectorized