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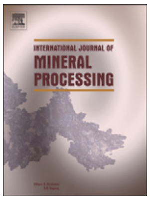

Discrete X-ray tomographic reconstruction for fast mineral liberation spectrum retrieval

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ABSTRACT

In mineral beneficiation, the mineral liberation spectrum of the plant feed conveys valuable information for adjusting operations, provided that it is available in minutes from particulate sampling. X-ray micro-tomography is the only technique available for unbiased measurement of composite particle composition (on a 3D basis). The bottleneck of current micro-tomographic systems is the X-ray scanning time (data acquisition) rather than the slice reconstruction time (data processing). An algorithm capable of reconstructing tomographic slices of composite mineral particles from a limited number of radiographic projections, thus significantly reducing the overall measurement time, is presented and demonstrated with numerical examples. The algorithm is cast around the *discrete algebraical reconstruction technique* and requires less than one tenth of the projection data needed by the currently used filtered back-projection methods, thus allowing a dramatic reduction of the scanning time.

1. Introduction

The metallurgical performance (metal recovery and concentrate grade) of an operating plant is determined by the liberation spectrum of the particles undergoing concentration and by the efficiency of the separation process. Ideally, maximum separation efficiency is achieved when particles are fully liberated. In practice, optimum liberation is always a compromise between ore mineralogy and energy required for comminution. The latter is often the most energy intensive and costly operation thus capable of compromising the profitability of the entire beneficiation process. In this contest, the possibility to assess the mineral liberation in the feed to the plant is a key factor for tuning the grinding systems at one side and to adjust the separation circuit at the other side. The potential of process mineralogy and automated laboratory characterization is recognized both by academia and industry (Baum, 2014). In short, fast automated mineralogy is a necessary component of modern control strategies that are able to respond to fluctuations in grade, mineralogy and texture that can be detrimental to metallurgical performance.

The combined use of SEM measurements of areal-grades (QEMScan) or linear intercepts on transects (MLA) of polished sections of the particles is popular to assess mineral liberation. However, these methods provide biased estimates of liberation (Barbery, 1991). The stereological correction methods for converting (e.g. via kernel correction) these low dimensional measurements into volumetric grade distributions are complex and not well established procedures (Leigh et al., 1996; Chiaruttini et al., 1999). In addition, these kernel correction procedures require time consuming sample preparation and measurements and are not free of error.

The use of X-ray micro-tomographic systems specifically designed for this purpose is very attractive. The principle of X-ray computed tomography is conceptually simple: the X-rays are attenuated differently while traversing the composite particles. The intensity of the X-ray signal is converted by a scintillator into light and recorded by a camera as a radiographic digital image. The object is then rotated by small angular steps and the radiographic operation repeated each time until completing full rotation. The collection of several hundred projections is employed to reconstruct the inner structure of the particles.

Commercial tomographic system are available from a number of makers but a tomographic system can easily be built in-house by assembling the three basic components (one cone beam micro-focus X-ray source, one traditional CCD or CMOS based X-ray digital camera or flat panel, and one precision air-bearing rotation stage) in a lead-wall cabinet for X-ray shielding.

Prof. J. Miller's research group at the University of Utah introduced the micro CT system into the mineral processing laboratory (Lin and Miller, 1996; Miller and Lin, 2003). Today this technique is recognized as being capable of supporting the engineers in the study of a number of particulate processes encountered in mineral- and hydrometallurgy-operation. It has been used in typical mineral processing analysis such as washability and mineral liberation, to observe particulate leaching advancement (Dhawan et al., 2012), to evaluate

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separation efficiency, to observe filter-caking formation (Lin and Miller, 2000), to reconstruct the full morphology of porous rocks and to simulate fluid multiphase flow through pores and throats (Casagrande et al., 2014; Piller et al., 2009). In short, micro CT is helpful where information on the inaccessible internal composition of particles is necessary to supplement the biased observation conveyed by measurements on particle surfaces or on low-dimension particle sectioning (i.e. linear intercepts or areal grades). Low dimension measurements invariably overestimate the liberation: they could see only one phase in a two-phase particle. This new quantitative tomographic technique is now available in a few leading mineral laboratories but once disseminated and with well-established operating protocols it will be capable to provide data superior to those traditionally provided by mineralogical observations on particle-sections or to supplement their information content. The micrometric spatial resolution of X-CT and the capability of detecting low density-contrast permits 3D textural characterization. The authors of this paper have also explored the use of CT both at synchrotron beam-lines and with laboratory micro-focus sources (Schena and Montanari, 2003, Schena et al., 2007). Its potential for sorting and micro-diamond detection was also explored (Schena et al., 2005).

Unfortunately, the current tomographic systems are not yet fast enough to provide liberation data in a few minutes or less, as desirable for a practical use in plant operations. The bottleneck is the scanning time required to take a sufficient number of radiographic projections with a full coverage around 360° of the rotating sample. Often, several hundred projections are needed to be taken to satisfy the minimum sampling requirements of the filtered back projection (FBP) algorithm that is the standard slice reconstruction method. The minimum number of projections prescribed to strictly respect the Nyquist sampling frequency principle is: number of projections$= \frac{\pi}{2}D$, where D is the diameter of the object in pixels. Today, the tomographic slice-reconstruction time is not a hurdle as in the past; many commercial codes are implemented on graphic board hardware for the fast processing of the radiographic projections to reconstruct the slices. It is the high number of projections required for reconstruction which still is an issue.

Roughly, one can envisage that even with a routinely and well-established workflow protocol for sampling, scanning, reconstructing and post-processing the tomographic digital volume, not less than a few hours are necessary for having the liberation data available for decision making. Most of the time burden is ascribed to X-ray scanning. When the number of projections is less than the prescribed minimum, the filtered back projection yields a reconstruction that is pathologically affected by radial streak artifacts and unsuitable for automatic image analysis procedures.

The alternative strategy proposed herewith is to reconstruct the tomographic slices with a method that is much less demanding in terms of number of radiographic projections and thus appropriate to cut the scanning time and in turn the overall time required for having usable liberation data. The method uses prior-knowledge of the attenuation of the mineral species that can be easily acquired with one single standard tomography. The novelty proposed is in the slice-reconstruction algorithm. Therefore, the method does not require any modification of the hardware of the existing tomographic scanning machines. Indeed, prior knowledge of the single mineralogical species allows introducing the additional constraints needed to significantly reduce the number of projections required for a high quality segmented reconstruction.

2. Discrete algebraical reconstruction technique

Rather than de-convolving the integral information content of the projections with the inverse of the Radon transform and its filtered back-projection implementation (Xiaochuan Pan et al., 2009), we set-up the slice image reconstruction problem according to the so called algebraical reconstruction technique (ART). We aim to reconstruct the image by minimizing the difference between the given projection data acquired from scanning and the (forward) projections of the image under reconstruction. The data fidelity (equality) constraint is written as a linear set of equations where the right side is the projection data (see Eq. (1) in the next section). The sketch in Fig. 1 illustrates the correspondence between pixels and coefficients of the linear equations according to the ART framework. For illustration purposes only horizontal ($\theta = 0°$), diagonal ($\theta = 45°$) and vertical ($\theta = 90°$) rays are shown. The pixels of the 4×4 sought image are row-wise numbered from 1 to 16. The continuous ART is also known as Projections onto Convex Set (POCS); the convex set is defined by the constraining hyper-planes. One commercial implementation of ART for continuous tomography exists (www.digisens3D.com).

When the solution sought should take discrete values the method is referred to as Discrete Algebraical Reconstruction Technique (DART). A vast literature exists on the DART methods where a binary (0,1) solution is required (Herman and Kuba, 2007), e.g. for applications where it is required to discriminate between one material and voids. Much less literature exists for applications similar to that proposed in this paper where liberated particles and composite particles made up of more mineral species are to be segmented based on their different X-ray attenuation as recorded by the projections (van Aarle et al., 2012; Batenburg and Sijbers, 2011) by discrete tomography techniques.

The constraint prescribing that the sought image should contain pixels taking luminosity in a small discrete set is an extremely valuable a priori information and allows to reconstruct using few tomographic projections.

2.1. Numerical method

The number of columns of the ART system matrix is the number of pixels of the square ($N \times N$) image to reconstruct (see Fig. 1). The number of equations is the number of rays times the number of projection angles.

Formally, for continuous tomography, the ART equality constraints are:

$$Sx = p \quad \textit{or} \quad \sum_{j=1}^{N^2} s_{i,j}\ x_j = p_i \tag{1}$$

where:

x is the column vector of pixel values of the sought image, the $((n-1)N + m)$-th entry of x is the (n,m)-th pixel location of the $N \times N$ slice image,
S is the sparse, real-valued matrix of the severely underdetermined tomographic reconstruction problem,
p is the projection vector.

In short, the ij-th element of the system matrix S is non-zero if the i-th ray beam passes through the j-th pixel. Normally the sample undergoing tomography is a cylinder then only the coefficients corresponding to a disk contained in the square image domain of the slice are non-zero. S is sometimes referred to as tomographic projection matrix. The element $s_{i,j}$ is the contribution of the pixel j to the measurement i, and it is the intersection length between the pixel j and the projection ray i, $\sqrt{2} \geq s_{i,j} \geq 0$.

In practice, in an operating plant the mineral species and their attenuation are known and the sought slice image has a discrete number of gray levels. Thus the pixel values in the vector x (see Eq. (1)) are bound to take discrete values. The discrete nature of the image constitutes an element of simplicity that is capable of further constraining the solution of Eq. (1). Thus transforming the continuous ART into a Discrete ART (i.e., DART) reconstruction problem.