Linear Iterative Phase Retrieval for Dual-Energy X-ray Imaging

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Keywords: Dual energy, radiography, phase contrast, phase retrieval, density, atomic number.
Summary: We propose a method to extract the material properties of density and atomic-number from single-distance, dual-energy imaging of both strongly and weakly attenuating multi-material objects with polychromatic X-rays. The method, referred to as linear iterative phase retrieval (LIPR), incorporates the Alvarez-Macovski (AM) model for X-ray attenuation. A simplification of this using an unorthodox interpretation of data-constrained modelling (DCM) technique is also presented. A comparison to the Paganin single-material phase retrieval algorithm [1] is presented in both simulation and experiment.

1. Introduction

X-rays passing through a sample acquire a "phase shift." In an aberrated imaging system this phase shift can show up as phase-contrast (or refraction) signals at the detector. The quantitative analysis of this signal is "phase retrieval". The phase-retrieval problem is in-general under-constrained and requires additional assumptions or measurements to solve uniquely. These assumptions generally place restrictions on the type of X-ray/sample interactions [1, 7]. We first demonstrate the undesired blurring or over-sharpening that occur when these assumptions are not met, such as when using a single-material method on a heterogeneous sample. In particular we consider samples that produce "reverse fringing" where the attenuation gradient is the reverse of the phase gradient. This can occur at a boundary between two materials where one is higher in density and the other is higher in atomic number. Here we formulate a single-propagation-distance, dual-energy phase-retrieval algorithm for the Fresnel near-field region by combining i) the Alvarez-Macovski model [6] for X-ray attenuation, with ii) the transport-of-intensity (TIE) finite-difference near-field approach [8]. First, we present our novel linear iterative phase-retrieval algorithm (LIPR) that extends the validity range over both the Paganin single material [1] and the data-constrained modelling (DCM) [7] methods. We demonstrate that this method can solve the phase retrieval problem in the presence of the "reverse fringing" discussed above. Then we show LIPR gives a satisfactory solution for this problem.

2. Methods

The Paganin single-material method assumes the interaction of the X-rays with the sample is described by a single unknown parameter: the sample's effective thickness. Another approach to overcome the lack of a unique solution is to take measurements at two or more propagation distances [3]. However, practical considerations such as alignment and detector utilisation make this approach ill-suited to many lab-based X-ray imaging systems, especially those using high geometric magnification such as the Heliscan micro-CT [4].
Our LIPR approach is suitable for cone-beam X-ray imaging of samples with an unknown, highly-heterogeneous composition. We take measurements using two distinct incident energy spectra, with a single fixed propagation distance. We overcome the non-uniqueness of the dual-energy phase-retrieval problem by assuming that the sample interacts with X-rays only via photoelectric absorption and Compton scattering. This assumption is valid for X-ray in the 10-120 keV energy range [5] as first presented by Alvarez and Macovski [6]. The dual-energy phase-retrieval problem is then reduced to a uniquely solvable (but nonlinear) state: two energy measurements are used to solve for two unknowns (photoelectric absorption and Compton scattering profile). This problem is linearised by an unorthodox interpretation of the existing Data constraint modelling (DCM) approach [7], by assuming the sample can be separated into two pseudo-materials and the detected signal to be a linear combination of each component. One is defined as the Compton scattering profile, and the second as the photoelectric absorption profile. According to the Alvarez-Macovski attenuation model, these materials respectively correspond to i) the projected density times atomic number cubed, and ii) projected density. However such linear separation of these two components is not always possible. Each iteration of the LIPR approach is numerically equivalent to this "re-interpreted" DCM, but generalised to avoid assuming the separation of the two pseudo-material components in the object. There are three parts to the LIPR method: (1) Calculating the current error using a forward model, (2) linear update iteration using the Jacobi iterative solver, and (3) the overall multi-grid scheme (to speed up the convergence towards a global optimal solution).

3. Results

For simulation, we show the phase retrieval results under the noisy case with the carbon and Sodium Iodide solution. For the real data, we show the phase retrieval results of diamond, and magnesium.

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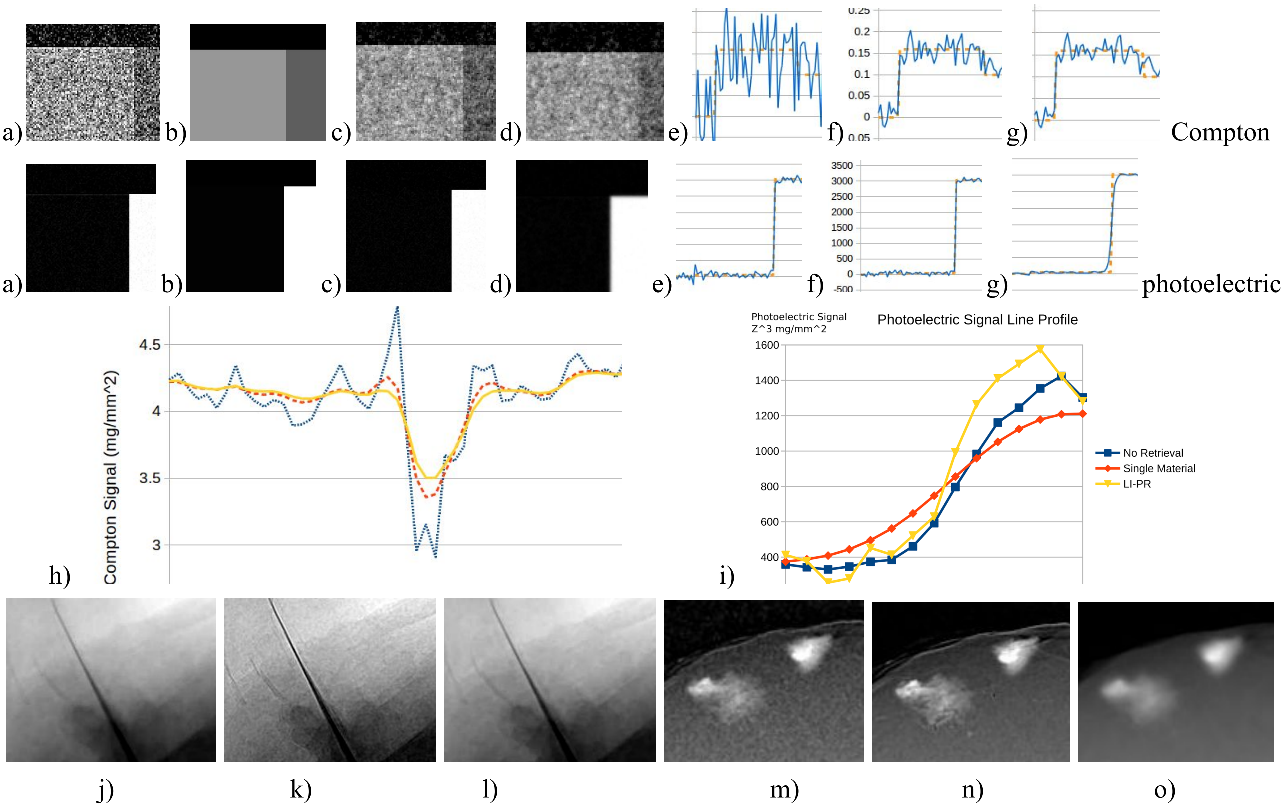

Fig: Retrieved Compton (top) and photoelectric signal (bottom): a,e) no retrieval, b) original, c,f) LIPR, e,g) single material. Note that the LIPR method preserves the de-noising effects of the Paganin single-material method, whilst avoiding the resultant over-blurring of the boundary. Line profile of real-data phase retrieval (yellow = LIPR, red = Paganin, and Blue = no retrieval). Real Data Compton signal: j) LIPR, k) no retrieval,l) single material. Real Data Photoelectric signal: m) LIPR, n) no retrieval, o) single material.

4. Conclusion

We have demonstrated the fixed distance near-field phase retrieval in multi-energy has a unique solution using the Alveraz and Macovski attenuation model [6] combined with the TIE formulation [8], and that this solution can be found by using our proposed LIPR method. Phase retrieval algorithms can be used to reduce both the phase artefacts and the noise of both signals (see Fig). Correct assumptions are required for successful phase retrieval; the single material assumption can not correctly retrieve reverse phase contrast in the photoelectric signal. LIPR obtains the correct Compton and photoelectric signal for simulation (Fig. a-g) and an improved result for real data (Fig. h-o). LIPR corrected the reverse phase contrast between diamond and magnesium, evident in Fig i) and m-o), while being more robust to noise compared to no retrieval.

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