



Material specific X-ray imaging using an energy-dispersive pixel detector



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ABSTRACT

By imaging the X-ray spectral properties or 'colours' we have shown how material specific imaging can be performed. Using a pixelated energy-dispersive X-ray detector we record the absorbed and emitted hard X-radiation and measure the energy (colour) and intensity of the photons. Using this technology, we are not only able to obtain attenuation contrast but also to image chemical (elemental) variations inside objects, potentially opening up a very wide range of applications from materials science to medical diagnostics.

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1. Introduction

Traditional radiography is based upon the transmission of X-rays through an object. The resultant radiograph represents the differential absorption of X-rays by the materials that make up the object. This has been the norm for over 100 years of X-ray imaging however the structural and chemical information carried by the X-rays of different wavelengths is not utilised in any way. Dual-energy techniques capturing high and low energy X-rays has enabled pseudo colour coded materials discrimination which is now widely employed in airport security scanners. Recent developments in X-ray photon counting detectors, has led to the ability to be able to distinguish X-ray colours directly, that is, the capability to image over specific spectral bands using the same detector, which can provide much more information about the composition and the environmental state of the object [1–5]. The measurable spectral bandwidth is an important metric since very wide bands (e.g. covering several keV) provide only crude material specific information, whereas very narrow bandwidths (e.g. hundreds of eV) would open up the possibility to identify individual spectral features like absorption edges or emission lines. Such narrow bandwidth detectors which also have the ability to cover a wide wavelength continuum are termed *imaging spectrometers* which

record 'hyperspectral' images (pixelated imaging data with a spectral domain [6]). In this research we use an X-ray imaging spectrometer to look at the absorbed and emitted radiation, and measure the energy (colour) and intensity distribution of the X-ray photons. We demonstrate how using these methods we can distinguish, identify and image specific materials inside large bulk objects using hard X-rays in a laboratory system.

2. Experimental

The laboratory experimental set-up for X-ray colour imaging is shown in Fig. 1. The X-ray imaging spectrometer consists of a 1 mm thick CdTe single crystal detector ($20 \times 20 \text{ mm}^2$) bump-bonded to a large area ASIC packaged with a high performance data acquisition system. The detector is cooled to approximately 8°C and operated under an applied bias voltage of -500 V . It has 80×80 pixels with a pitch of $250 \mu\text{m}$ and an energy resolution (FWHM) of $\sim 800 \text{ eV}$ @ 59.5 keV and $\sim 1500 \text{ eV}$ @ 141 keV [4]. During operation each photon event has its energy and pixel position and the frame in which it occurs recorded. Events are processed and histogrammed according to measured energy, using a total of 400 bins (0.25 keV per bin). During this process, an event-sharing strategy is employed to correct events where a photon interacts between neighbouring pixels and cause it to deposit fractions of the total energy between neighbouring pixels. The detector operates at a maximum frame rate of 10 kHz and can support a maximum global count rate of around 10 Mcps with effective

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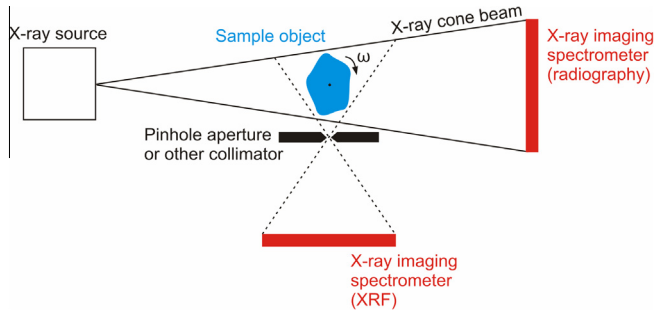


Fig. 1. Experimental set-up for laboratory based X-ray colour imaging. For radiography, the plane of the X-ray imaging spectrometer is placed perpendicular to the direction of the beam. In this case, ideally a low power microfocus source would be used. For XRF, the plane of the imaging spectrometer is placed parallel to the direction of the beam, where a pinhole or other collimator system is used to project an image. In this case, the source would ideally have a high flux, but is not required to be microfocus. Rotation of the sample object around the vertical axis (ω) can be performed for CT experiments.

charge sharing discrimination. Hyperspectral images were energy-calibrated such that each pixel has a common energy axis; the calibrations for each pixel were found from their response to known gamma emission lines from the radioactive decay of ^{241}Am .

Radiographic data was collected with the detector positioned directly behind the sample (plane of the detector perpendicular to the beam direction). In this case, a low power (3 W max.) micro-focus tungsten target X-ray tube was used as a source operating at accelerating voltages in the range 80–100 kV and beam currents of 1–2 μA . Exposure times were typically around 2 min with global count rates of around 10 Mcps.

X-ray fluorescence (XRF) data was recorded with the plane of the detector orientated parallel to the beam direction. A tungsten pinhole aperture (hole diameter 200 μm) was used to define an image of the sample object. In this case, we used a moderate power microfocus X-ray source (200 W max.) operating at similar acceleration voltages and anode currents of 400–450 μA . Exposure times were typically around 5 min with global count rates of around 150 kcps.

3. Results and discussion

Fig. 2 shows a colour X-ray radiograph of a 12 mm diameter glass bottle filled with iodine solution (2.5% w/v I; 2.5% w/v KI; 89% w/v ethanol). The data is presented as the calculated optical density as a function of X-ray energy, E , from the Beer–Lambert law:

$$\text{Optical Density}(E) = -\ln\left(\frac{I(E)}{I_0(E)}\right) = \mu(E)t \quad (1)$$

where I_0 is the intensity with no sample in place (flat field), I is the intensity with a sample in place, μ is the linear attenuation coefficient and t is the sample thickness. By summing over all the spectral bands we acquire a grayscale image similar to that obtained from a standard scintillator-based detector (**Fig. 2a**). The glass bottle and the liquid meniscus can be clearly seen in this image. Due to the hyperspectral nature of the data, multivariate methods can be applied to extract key information. In this case, principal component analysis has been used to create a colour composite image of the sample object (**Fig. 2b**) [7]. We can see how different materials are now colour segmented, more clearly identifying the liquid containing regions (pink) from the bottle walls (yellow). We can also inspect the individual pixel spectra to look for key spectral features that may give material specific fingerprints. **Fig. 2c** shows three spectra taken from different regions within the image. Region

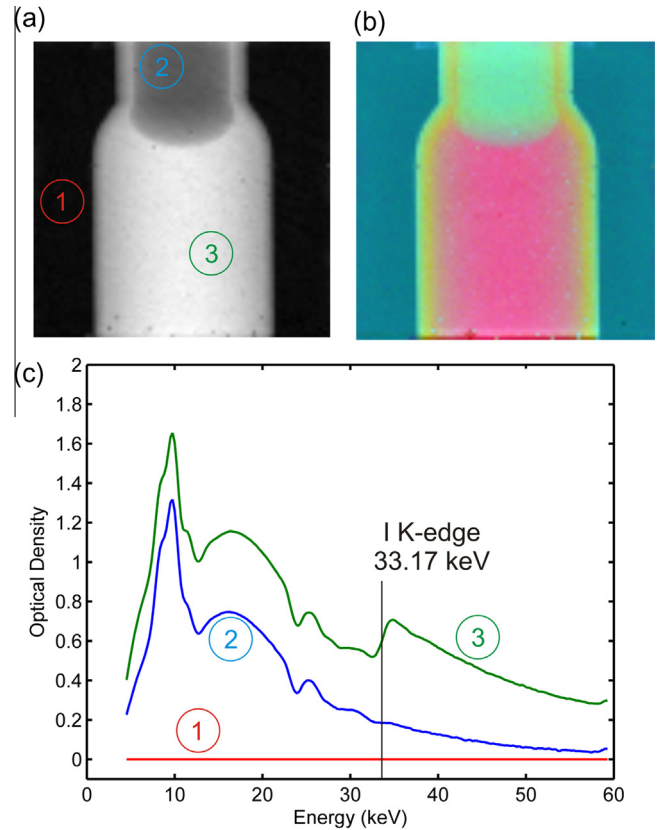


Fig. 2. Colour X-ray radiography of a glass bottle filled with iodine solution. (a) Grayscale image (sum over all spectral bands). (b) Colour composite image generated via principal component analysis. (c) Mean spectral profiles extracted from three separate regions: (1) Outside object. (2) Glass bottle. (3) Iodine containing regions.

1 is from outside the bottle, region 2 is from the neck of the bottle and region 3 is from the liquid. Outside the object (region 1) the optical density is zero throughout the spectral range, as would be expected. In regions 2 and 3 we observe non-zero optical density, with the liquid containing regions showing increased attenuation. Peaks at approximately 10 and 25 keV are from tungsten L emission lines (from the X-ray tube) and Cd/Te emission lines from the detector material itself. On calculating the optical density using Eq. (1), they arise from higher intensity in the denominator (I_0) at these energies, creating peaks in the calculated optical density. The spectrum from region 3 additionally also shows a step change in optical density at 33.1 keV which corresponds to the iodine K-edge, therefore confidently identifying this liquid to contain iodine.

It is also possible to perform 3D imaging using standard computed tomography (CT) methods. In this case, we recorded colour radiographs for successive sample rotation steps and then used the algebraic reconstruction technique (ART) to build the 3D volume [8]. Reconstruction was performed for every X-ray energy (i.e. on a channel by channel basis [9]) such that the resultant dataset has 4 dimensions (three spatial and one spectral) with each voxel containing an X-ray spectrum. We then applied multivariate methods and cluster analysis on this 4D dataset to segment the data based upon the spectral profile in each voxel [7]. This method is unique in that no thresholding is required, the segmentation is based upon the spectral properties alone rather than gray levels (as is the case for conventional CT). **Fig. 3** shows the 3D image of the iodine bottle example. We used a total of 60 projections around 360° (60 rotation steps of 6°) with 2 min

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