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Quantitative sorting using dual energy X-ray transmission imaging

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Abstract Dual energy techniques are well-known methods in X-ray transmission imaging. However they are not commonly used in a quantitative manner in sorting applications. We introduce a method called Basis Material Decomposition (BMD) that allows the determination of the fraction of mass of different, a priori known materials using two X-ray spectra and/or spectral detector efficiencies for dual energy X-ray imaging. The method exploits the dependency of the X-ray attenuation on density and atomic number of the object and the energy of the X-rays. One example is the quantitative sorting of pollutants from valuable material, e.g. halogens as bromine from plastics to enhance their recovery rate significantly. A possible application in mining is the detection and sorting of diamonds from the host ore kimberlite, allowing diamonds to be detected even if they are covered in mud or dust or completely enclosed in the ore. We present measurements from a lab setup and discuss how this approach can provide benefits in an industrial environment in the near future.

1 Introduction

Dual energy X-ray imaging is a method to obtain quantitative information from X-ray images for material characterization. To get this information, either two sets of images with different spectra need to be acquired or a detector system providing two energy channels needs to be used.

In X-ray imaging, two independent quantities of the object define the attenuation of X-rays: The atomic number and the areal density of the object to be penetrated. For a homogenous object, the areal density is the product of density and thickness; in general it is the projection of the density along the X-ray path. In radiographic images, the product of attenuation coefficient (which is material specific) and density are integrated along the X-ray path through the object. Thus they cannot be distinguished in a projection image without further knowledge. However, the attenuation coefficient depends on the energy of the X-rays. Therefore information on the type of material becomes available, if an object is imaged using different X-ray spectra or using an energy resolving detector. Such Dual Energy techniques have been known since the mid-70s [1] and are well established in medical imaging and qualitative applications as security scanning, but have not yet been commonly used in quantitative sorting applications or non-destructive testing.

In such a case, Basis Material Decomposition by dual energy imaging is a very powerful tool to overcome the limitations of standard radioscopy, as it provides quantitative information for given constituents, i.e. the areal density of the basis materials. These can be used to derive quantities as concentration or the total amount of each basis material can be calculated. Furthermore, it implicitly contains a beam-hardening correction that reduces the artifacts resulting from the thickness dependence of other dual energy techniques.

2 The method of basis material decomposition

The energy-dependent extinction $K(E)$ of a compound material is a linear combination of the attenuation coefficients $\mu_j(E)$ of the constituents (basis materials, indexed with j) weighted with their respective concentration.

$$K(E) = \sum \mu_j(E) a_j$$

where a_j is the areal density of material j. According to Lambert-Beer's law, the attenuated intensity I behind the object is

$$I = \int S(E) D(E)\, \mathrm{e}^{-K(E)} \mathrm{d}E$$

where $S(E)$ is the source spectrum and $D(E)$ is the spectral detector efficiency. Given that the spectral characteristics of the imaging system and the attenuation coefficents of the basis material $\mu_j(E)$ are known, it is feasible to obtain areal densities of the corresponding basis materials by either energy resolved measurement or two measurements with different X-ray spectra [2]. The spectral characteristics of the imaging system can either be measured or simulated from a physical model and the attenuation coefficients of the basis materials can be looked up from respective tables if the occuring materials are known.

3 Applications

3.1 Brominated plastics

For demonstration of the method, a typical waste sorting application was chosen: discrimination between regular plastics acrylonitrile butadiene styrene (ABS) and polystyrene (PS) and those containing brominated flame retardants with a bromine content up to 10%. In recycling of these products bromine is considerd as a contamination. For this example shredded bulk material will be considered, e.g. from the housings of consumer eletronics. Those pieces of plastic that exceed a given bromine content need to be sorted out.

Exemplarily, four pieces of plastic, ABS and PS, both pure and brominated, were imaged at different X-ray spectra. One of the standard radiographic images can be seen in Fig. 23.1. From these images, it is impossible to decide whether a part contains bromine or not, because it is impossible to distinguish whether higher absorption is caused by a higher bromine content or from greater thickness.

By using carbon and bromine as basis materials, the method allows to identify those parts containing bromine, which must be separated before recirculation of the remaining plastics. The bromine concentration image (Fig. 23.2) clearly shows the possibility to distinguish bromine free from bromine containing plastics. The bromine free parts almost vanish in the background of this image, because of their nonexistent bromine concentration.

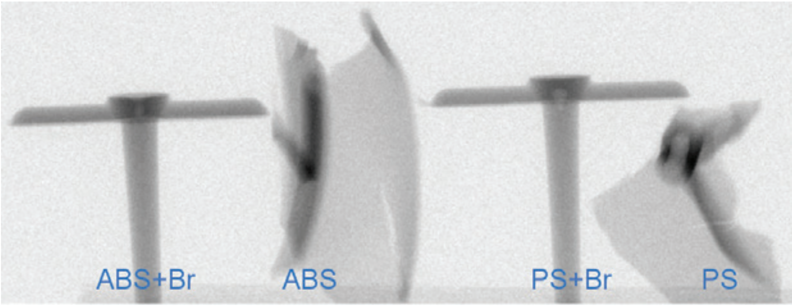

Figure 23.1: X-ray transmission image: brominated (ABS+Br, PS+Br) and bromine free (ABS, PS) plastics are not distinguishable from each other.

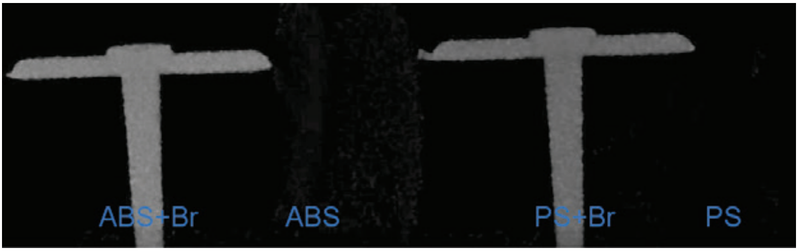

Figure 23.2: The resulting image of the bromine concentration of each particle. The plastics containing bromine can be distinguished from the others clearly.

3.2 Diamond detection

An other example is the detection and sorting diamonds from the host ore kimberlite. State-of-the-art technology use the X-ray exitation of fluorescence in the visible and UV range of electromagnetic radiation. Thus, only diamonds on the surface can be detected. Diamonds embedded in kimberlite or covered with dust and mud cannot be detected using that method.

This example is containing a diamond embedded in granulated kimberlite. It can be seen in Fig. 23.3: Two images at two different spectra are shown (80 kV and 120 kV). The diamond is not visible in either image. The resulting BMD images (Fig. 23.4) are shown in color. Black and blue denote no or low material, green indicates high content of the

Figure 23.3: The two images show the example of the diamond embedded in granulated kimberlite at two different spectra (80 kV and 120 kV).

Figure 23.4: The resulting BMD images, calculated from the images in Fig. 23.3, are shown in color. The left image represents the kimberlite content. The right image represents the carbon content and the diamond can be seen clearly.

respective basis material. The left image represents the carbon content and the diamond can be seen clearly.

4 Results

The applied dual energy analysis (Basis Material Decomposition) led to a positive separation of the respective basis materials in both cases. As shown above, both settings, diamond/kimberlite and plastics with-/without brominated flame retardants, reveal that the contrast in conventional acquisition (single spectrum) is very low or even nonexistent, making differentiation and recognition respectively hardly possible, especially for objects with varying thickness. Thereby a separation of the given materials is not possible using conventional methods while BMD has proven to be a powerful method in quantitative X-ray imaging.

It was possible to reliably detect a concentration of 5-10% of brominated flame retardand in plastics as ABS and PS. For the detection and sorting of diamonds in kimberlite, BMD allows to detect diamonds even if they are completely enclosed.

5 Summary and outlook

The method of Basis Material Decomposition is demonstrated to be a powerful method in quantitative X-ray imaging. In the application of sorting plastics with and without brominated flame retardants, it would be possible by BMD to systematically enrich the plastics fraction to a certain bromine content by monitoring and registering the bromine content of every single piece of the shredded plastic particle. This would give the opportunity to meet statutory limits safely while utilizing them most effectively. In a mining application, the introduced method allows to detect the diamonds in an earlier step of the chain of the crushing processes with decreasing grain size and thus can prevent large and very valuable diamonds to be crushed into small and less valuable parts in the following stage.

The Areas of application include, but are not limited to: mining, recycling, food industries etc. Currently an evaluation and comparison with other dual energy methods are being done. Different setups of demonstrators for industrial sorting applications are currently under construction. The analysis software containing the BMD algorithm will be trimmed for sorting application needs regarding processing speed and real time capabilities and will provide the flexibility for adaption to other areas of application, e.g. the food industry. The first tests in a lab setup are very promising, next step is the application to industrial conditions and investigations concering performance and stability under those conditions.

References

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