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Concentration determination for sorting applications using dual energy X-ray transmission imaging

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Abstract Dual Energy X-ray imaging is a method to provide quantitative information about the examined material. With Fraunhofer EZRT's Dual Energy technique it is possible to determine the concentration of a specific material in an object. This is realized through the Fraunhofer Dual Energy algorithm, which is using two X-ray spectra and/or spectral detector efficiencies for Dual Energy X-ray imaging. In this way, an areal mass density is obtained and the fraction of the mass of two given materials that differ in atomic number can be determined. This information can be used for material characterization. So X-ray Dual Energy can also be useful in industrial applications, for example to reduce the contamination of wood chips by plastic pieces. In general, differentiation is difficult in terms of gray values or shape. Here the Dual Energy method shows advantages. An overview on the method will be given as well as an introduction to current and future fields of application. The results from the test case of differentiating wood from plastics are presented and discussed.

Keywords: X-ray, dual energy, concentration of materials, separation of materials, material characterization, transmission imaging, radiographic imaging.

1 Introduction

Dual Energy X-ray imaging has proven to be valuable technique to acquire quantitative material properties from computed tomography (CT) or radiographic images. In contrast to standard measurements it is able to provide additional information about the atomic number (Z) or the density of the irradiated material. Since the 70's [1] these methods have been developed and evolved. Its main applications lies in medical and security applications like airport cargo scanner but it has not yet been commonly used in non-destructive testing (NDT). Its ability to determine the concentration of distinct materials within certain types of material compositions has widened its usage to different branches of application like sorting and recycling.

Dual Energy images are created by acquiring two X-ray images of the same sample at different spectral parameters. While standard X-ray images only allow to separate different materials on their attenuation of the X-rays and thereby struggle with varying radiation thicknesses, Dual Energy methods enable one to separate certain materials independently of the irradiated thickness of the specimens. Furthermore Dual Energy can be used to enhance the contrast of different materials which provide only low contrast in conventional X-ray imaging.

The ability to derive quantitative information from the images can also be used to calculate the concentration of materials in relationship to the entire specimen. This is of particular interest for several applications [2]. It can also be used to assert the presence of materials within hosting materials like diamonds in kimberlite [3].

2 Motivation

Single-variety separation of plastics is a crucial task for the sorting industry. This is especially true for black plastics which cannot be separated by optical techniques. Besides that, plastic contaminations in streams of material are challenging to detect and separate for other applications as well. In streams of biowaste for example plastic contaminations represent a crucial problem for the quality of biogas or humus production. Likewise the lumber industry is challenged by plastic leftovers or compound materials within the processed timber streams.

While the separation of wood from plastics provided promising results, some kinds of plastics could not be separated from wood. In order to categorize different types of plastics which can be separated from those which can't, very pure specimens of different plastics were measured and analyzed.

3 Dual Energy Method

Dual Energy in sorting or recycling tasks is primarily used to derive physical quantities from X-ray images. This is based on the fact that the total attenuation coefficient depends on the energy of the X-ray as well as on the penetrated material. In order to acquire X-ray images sufficient for Dual Energy algorithms at least two images of the same object with different spectral parameters have to be acquired. Different spectral parameters can be achieved by either changing the acceleration voltage of the tube (kV-Switching), using different filter materials for each image or by using a Dual Energy detector which is capable of acquiring two images at the same time. Changing the filter between two acquisitions is hard to achieve in industrial sorting environments and is therefore impracticable. Rapid kV-Switching is possible in sorting applications but requires exact timing of the system and is limited in regards to belt speed and lifetime of the system. It is however used for Dual Energy attempts for CT. The commonly used method for sorting on belt or chute systems is therewith the usage of Dual Energy detectors. When processing Dual Energy algorithms, information based on the penetrated material can be obtained. In fact Fraunhofer EZRT Dual Energy algorithm is able to derive the areal density ρ for two materials from those measurements. Based on this calculated areal density it is possible to calculate the concentration of one of this materials within a compound of different materials.

This is based on Lambert-Beer's law describing the attenuated intensity after an object as

$$I = I_0 * \exp(-\mu' * \alpha) \tag{7.1}$$

where μ' is the attenuation coefficient, α the areal density and I_0 the non-attenuated intensity. While penetrating more than one material at a time, the attenuation coefficients sum up. Acquiring two (or more) images at different spectral parameters leads to a set of similar equations which describe the extinction of the same material at different energies. This leads to

$$I_k = I_{0k} * \exp(-\mu'_{jk} * \alpha_j) \tag{7.2}$$

where k indexes different energies and j being the index of the material. This approach summarizes all X-ray attenuation effects which includes Compton scattering and photo-electric absorption.

When using a non-monochromatic X-ray source the intensity captured by the detector can be described utilizing the detector efficiency *D(E)* and the emitted spectra *S(E)*

$$I_0 = \int dE * S(E) * D(E) \tag{7.3}$$

In order to utilize this attempt the used spectra and the detector efficiency has to be known. This dates can be achieved by simulation or measurement techniques. While measuring is tougher than simulation it may lead to better results. Using this in the equation above leads to:

$$I = \int dE * \exp(-\mu'(E) * \alpha) * S(E) * D(E) \tag{7.4}$$

With obtained spectra *S(E)* and detector efficiencies *D(E)* the areal densities α_j can be calculated. This requires a selection of materials upfront. Using this for two materials leads to two equations with can be solved under certain conditions and result in two areal densities for those chosen materials. This also enables the calculation of material concentrations.

4 Measurement setup and specimens

In order to perform measurements based on industrial environment the specimens were measured in movement using a drawer system mounted on a linear xy-axis system. The system as well as the used Dual Energy line scan detector (C10800-09FCM-C) were provided by Hamamatsu. All tests were performed using a high power X-ray source with an acceleration voltage up to 225 kV. To compare also the method of kV-Switching to the results gathered from the Dual Energy detector, repetition measurements with varying kV were used. All specimens where analyzed using 50kV, 70kV and 100 kV. Dual energy measurements where performed analyzing all three different spectra. For rapid kV-switching the acquired projections where registered and only the low-energy channel was used to compare different accelerating voltages. The first application to be analyzed was the detection of contamination of wood by plastic pieces. In this case the type of the plastics is unknown. It is not necessary to identify different types of plastics, only the separation from wood is important. In order to characterize different types of plastics and make a assertion about which can be separated from wood, pure plastic specimens of the following types were analyzed as well. Table 7.1 describes the different types of plastics used for the analysis.

Table 7.1: Different types of plastics used for the analysis.

Specimen	Density ρ [g/cm^3]	Grain size [μm]
UHMW-PE	0.94	150
UPVC	1.4	250
PS	1.05	250
PMMA	1.19	600
PTFE	2.2	675

5 Results

To separate plastic leftovers from wood the provided pieces were irradiated and analyzed. Figure 7.1 shows the plastic pieces on the left and the wood chips on the right. Both materials provide a similar contrast in a standard X-ray radioscopy image. A differentiation between both materials can hardly be achieved.

The resulting X-ray Dual Energy image of higher Z material is shown in Figure 7.2. While the lower Z-materials blur out of the image, higher Z-materials appear brighter. All plastics except the one in the upper left corner appear bright in contrast to the wood, which appears dark in this image. Using Dual Energy analysis the differences between atomic numbers of the specimens clearly enhanced the possibility to separate both types of material to a certain amount.

Since not all plastic types could be separated from the wood, measurements with different pure and known plastics were performed to determine how good the separation of plastics and wood with the Dual Energy method works. Table 7.1 displays the used materials and their densities. The plastics were fine grained and uniformly filled in a culture dish so that the fill level of all plastic samples was similar.

Figure 7.3 displays the Dual Energy results of the pure plastic specimens in pseudocolor. The specimens contained in the culture dishes are the following from left to right:
Top line: rubber, PMMA and wood sample;
Bottom line: PTFE, UPVC, UHMW-PE and PS.

The pseudocolor image indicates differences between some of the specimens but also shows that certain types of plastics seem not to be distinguishable using Dual Energy. While rubber, PTFE and UPVC seem to be clearly separable from wood and the other three specimens (PMMA, UHMW-PE and PS) the specimens on the right side of figure 7.3 show only minor differences among themselves. They also only display minor differences in respect to the wood sample.

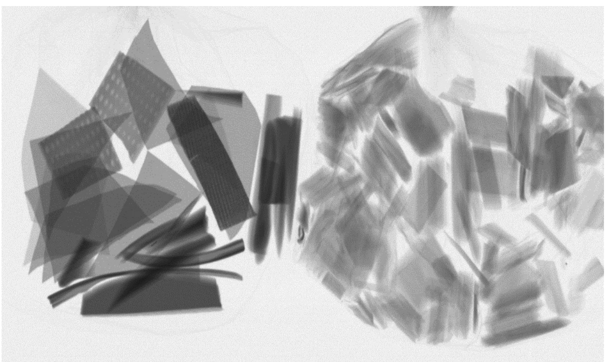

Figure 7.1: X-ray image of plastic pieces (left) and wood chips (right).

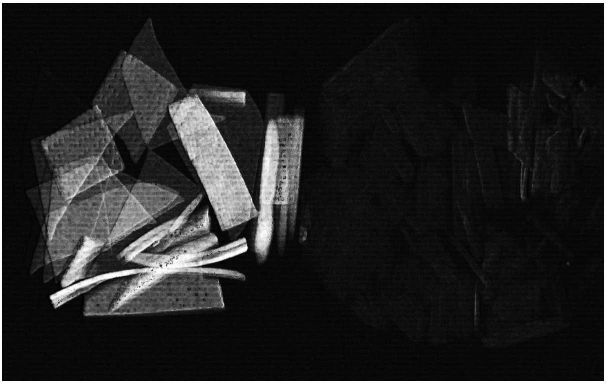

Figure 7.2: Dual Energy X-ray image showing higher Z material (higher atomic number). Most plastics appear bright.

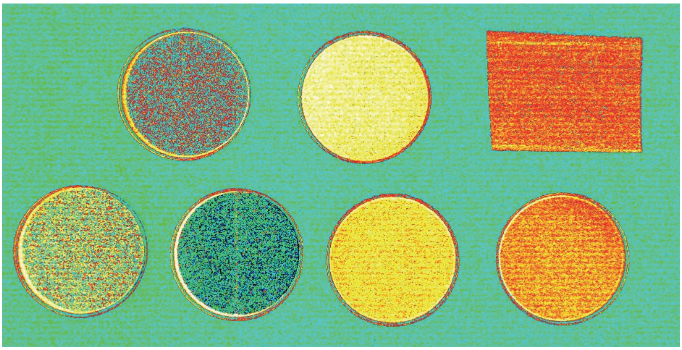

Figure 7.3: Pseudocolor image of different plastics displaying the areal densitiy using both energy channels of the detector.

It is to consider that the height of the specimen and thereby the irradiation path is known in this laboratory measurements. While the output of the Dual Energy algorithm is the product of material height and density, this additional information is key to separate those materials. In industrial environment scraps of varying size must be processed. Separability under this circumstances is only achievable if such additional information is available. This could be obtained by optical measurement systems for example.

In comparison to the results from the Dual Energy detector, figure 7.4 illustrates the areal density for the same specimen using kV-switching. As with the results from figure 7.3 UHMW-PE and PS are hard to separate from the wood sample. In addition PTFE appears homogeneous in its areal density and is also not easily separable from wood. For our setup, test samples and algorithms kV-switching does not offer any advantages over the direct usage of both Dual Energy detector channels.

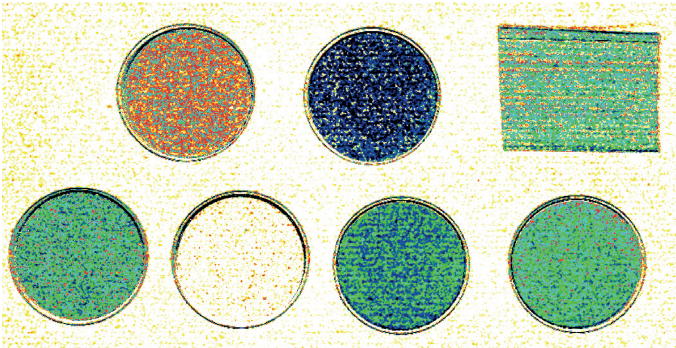

Figure 7.4: Pseudocolor image of different plastics displaying the areal density using different energies on the same detector channel.

6 Summary

While first tests indicate that the separation of plastics from wood seem to be achievable, testing distinct and pure plastic specimen outlined that this may not be possible for all kinds of plastic samples. In order to enhance the capability of separation additional information like the height of the sample is needed. This could be achieved utilizing optical measurement systems and seems to be practicable in industrial application as well.

The results provided by the measurements using (rapid) kV-switching seem not to compensate for the fact that it is hard to accomplish in sorting environments and moving systems. It may however proof valuable for CT applications.

7 Outlook

As indicated by the results, it is not ultimately clarified that all sorts of plastics and wood can be separated. Though the results are promising, there have to be further investigations with real industrial specimens. To find out if the results are reliable enough for industrial applications, the influence of the height of the object has to be clarified.

Another point which should be examined is the influence of the speed of the system to the accuracy of the imaging. The standard industrial belt systems use high speeds (approximately 3-3.5 m/s). Increased belt speed may lead to a lower SNR in the acquired images and therewith reduce the precision of the attached Dual Energy algorithms.

Also the measurements comparing kV-Switching and Dual Energy imaging need to be investigated further to get a reliable information about the advantages of each method for industrial applications. The results with the used Dual Energy line scan camera showed no advantages using kV-switching, but these could possibly be achieved using other types of detectors or sources. The respective advantages and possibilities of these two methods are thus under investigation.

Acknowledgement

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