Plastic sorting by X-ray radioscopy with photon counting detector

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Abstract
Plastic sorting technique is of great importance to avoid major environmental and health problems. Acrylonitrile-butadiene-styrene (ABS) is a commonly used thermoplastic polymer that often contains flame retardant (FR). The present work investigates the decomposition feasibility of different ABS-FRs using X-ray radioscopy with photon counting detector. We build a phantom that contains 3 ABS-FR materials and a PCD array with 6 energy bins. A material decomposition method based on patchwise regularization and least log-squares is proposed and evaluated. Results show that the proposed method can not only separate 3 ABS-FR materials but also obtain high quantification accuracy of the basis materials.

Keywords: plastic sorting, photon counting detector, X-ray, material decomposition

1 Introduction
Waste electrical and electronic equipment (WEEE) has been increasing rapidly due to the development of electronic industry. In European Union, the amount of WEEE generated in 2005 is 9 million tonnes and this number is supposed to grow to 12 million by 2020 [1]. The sorting technique is important for subsequent treatment and recycling of WEEE to avoid major environmental and health problems. Acrylonitrile-butadiene-styrene (ABS) is a commonly used thermoplastic polymer that often contains flame retardant (FR) [2]. The present work investigates the decomposition feasibility of different ABS-FRs using X-ray radioscopy with photon counting detector (PCD). PCD is able to characterize photons having different energies and makes it possible to separate various materials with a single acquisition. To set up this study, we build a phantom that contains three ABS-FR materials for simulated radioscopy imaging. We propose a material decomposition method based on regularized least log-squares criterion for the objective function and evaluate its performance for ABS-FR materials identification.

2 Method
Let \( \mu(E, \bar{x}) \) denote the linear attenuation coefficient of a point at location \( \bar{x} \) within the object under energy \( E \). For a mixture object, if we choose a basis of \( M \) materials, then \( \mu(E, \bar{x}) \) can be considered the linear combination of these materials’ mass attenuation coefficients \( \mu_{m\alpha}(E) \) [3] weighted by their densities \( \rho_{m\alpha}(\bar{x}) \), where \( \alpha \) denotes the type of material. According to Beer-Lambert law, the expected number of photons \( \lambda_i(\alpha, \bar{x}, E) \) at pixel \( (px, py) \) in energy bin \( B_i (i = 1, 2, ..., N) \) with \( N \) indicating the total number of energy bins) with the start energy of \( E_i \) and final energy of \( E_f \) can be expressed as:

\[
\lambda_i(\alpha, px, py) = \sum_{E_i(i)} N_{0i}(E) \exp \left( - \sum_{\alpha=1}^{M} P_{\alpha}(px, py) \mu_{m\alpha}(E) \right), \quad \text{with} \quad P_{\alpha}(px, py) = \int \rho_{\alpha}(\bar{x}) ds \]

where \( N_{0i}(E) \) is the initial number of photons of X-ray spectrum at energy \( E \). A log-squares criterion has been introduced in [4] for the objective function to obtain \( P_{\alpha}(px, py) \). Based on this formula, we propose to add a patchwise regularization term in the objective function:

\[
P_{\alpha}(px, py) = \arg \min_{P_{\alpha}(px, py)} \left\{ \sum_{(px, py) \in C} \sum_{i=1}^{N} \left[ \ln(\lambda_i(\alpha, px, py)) - \ln(m_i) \right]^2 + r R(P_{\alpha}(px, py)) \right\} \]

where \( C \) represents a small patch of the acquired image, \( r \) is a relax parameter and \( R(P_{\alpha}(px, py)) \) is the regularization term that considers the total variation of \( P_{\alpha}(px, py) \) within patch \( C \).

In the present study, the object is supposed to be isotropic and X-rays are nearly parallel. Therefore, after obtaining \( P_{\alpha}(px, py) \) for each pixel, we decide it by the depth of object to calculate \( \rho_{\alpha}(\bar{x}) \).

We use INSA software Virtual X-ray imaging (VXI) [5] to simulate the radioscopy process of different ABS-FR materials. Figure 1 shows the system scheme. The phantom is composed of 3 cubes with height of 10 mm, width of 10 mm and depth of 2 mm, representing different ABS-FR materials. The detailed components of each cube are listed in Table 1. The simulated
3 Results

In view of the material composition of the object, we choose ABS, bromine (Br) and chloride (Cl) as a basis of materials. The reason for having not selected phosphorus as the basis is that P and Cl have too close atomic numbers and experiments showed that they can be barely separated. Patch size for regularization is set to be 2x2. Figure 2 demonstrates the decomposition results of the scanned phantom. All three cubes are visible in Figure 2 (left), due to the containment of ABS. The ABS+TBBPA cube is well separated and highlighted in the Br basis image (middle). The other two tubes all appear in the Cl basis image (right), but there exists significant density difference between them, therefore they can be easily distinguished by the observer even if the concentration of FRs changes more or less. Figure 3 gives the 1-D profile along dash lines in Figure 2, the comparison between theoretical densities (see Table 1) of 3 basis materials and our measurements is illustrated. Their high consistence indicates that the proposed method can not only separate 3 ABS-FR materials but also obtain high quantification accuracy of the basis materials.

<table>
<thead>
<tr>
<th>Table 1 Components of materials in the 3 cubes</th>
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<tbody>
<tr>
<td>Material (ABS+FR)</td>
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<tr>
<td>-------------------</td>
</tr>
<tr>
<td>TBBPA</td>
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<tr>
<td>DDC-CO</td>
</tr>
<tr>
<td>RDP</td>
</tr>
<tr>
<td>Fr.</td>
</tr>
<tr>
<td>15%</td>
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<tr>
<td>ρ_eff of Br, Cl and P, resp</td>
</tr>
</tbody>
</table>

TBBPA: tetrabromobisphenol A  
DDC-CO: dechlorane plus  
RDP: resorcin bis (diphenyl phosphate)  
ρ_eff: efficient density (ρ_{material}×mass %)

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References


