Recognition of PET bottles in highly efficient advanced reverse vending machines by Vis-NIR spectral imaging

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Introduction

Polyethylene terephthalate (PET) is the most valuable of all domestic plastics because it is high-grade interlaced. The raw materials for PET are sourced from mineral oil or coal. Nowadays a blend of virgin and recycled PET, in the range of 50%, is employed to manufacture new PET items to preserve raw materials. With regard to beverage bottles, a bottle-to-bottle-cycle will soon be introduced in many industrial countries. The beginning of the bottle-to-bottle-cycle is the collection of bottles. Automated collection is supported by so-called reverse vending machines (RVM).

The two most important tasks of RVMs are the (1) recognition and (2) counting of PET bottles, in order to give a pledge value back to the customer. To discriminate PET bottles from other unwanted items in the input stream of a RVM, a new material selective sensor system has been developed based on spectral imaging in the 750–980 nm wavelength range of the visible to near infrared (Vis-NIR) spectrum. Apart from the classification of spectral signatures of different kinds of plastics by spectral imaging, the diffuse radiation from the item's surface has been employed to receive 2D grey-scaled pictures of the input stream to calculate the centre of gravity of items for steering blow-off valves and for removing unwanted parts from the stream.

In this paper, the authors describe the fusion of spectral imaging with digital image processing. For digital image processing, the grey-scaled images of a CMOS-based Vis-NIR spectral imaging system were exploited to detect connected components for counting of PET items. The advantages of CMOS-arrays compared to InGaAs-arrays are manifold in economic sense. CMOS detectors have a wide performance range, are cheaper and more readily available.

Materials and Methods

Characteristic features in PET spectra can be found from the fundamental molecular vibrations up to the third overtone region. The intensity values of the third overtones are still high enough for robust detection with well-suited CMOS semiconductor arrays. For PET bottle recognition, a new spectral imaging system from Inno-Spec GmbH, termed "N²IR", has been applied. The system consists of a transmission spectrograph with an optimised lens arrangement for the 750–980 nm wavelength range and a monochromatic CMOS-camera.[1, 2] The technical details of the spectral imaging system "N²IR" (Figure 1) are listed in Table 1.

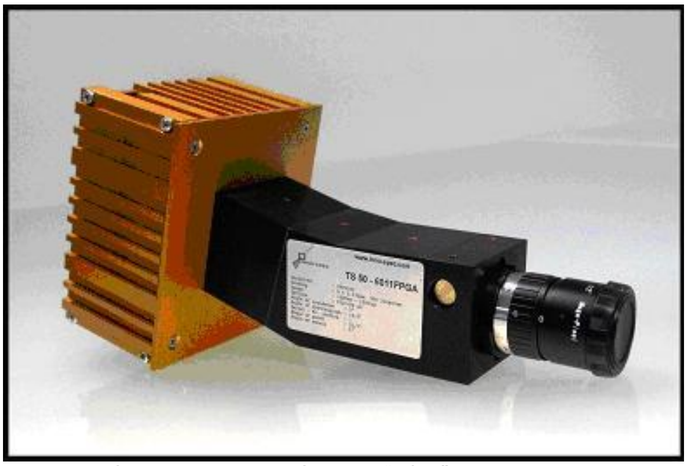

Figure 1. Spectral Imaging System "N²IR".

Table 1. Technical specification.

Spectral range	750–980 nm
Pixel dispersion	70 nm mm^{-1}
Spectral resolution	9 nm (FWHM)
Slit width	50 µm
Slit length	14 mm
Semiconductor sensor	5 Mpx CMOS
Pixel (spec. x spat.)	2.592 x 1.944
Pixelrate	96 Mpx s^{-1}
Intensity digits	12
Data transfer	Gigabit-Ethernet
FPGA	Spartan 3E
Operating voltage	24 V

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By disregarding the spectral information of the reflected radiation it is possible to receive a grey-scaled image by connecting the observed line scans to 2D pictures. These pictures have been analysed by methods of digital image processing to separate geometrical contours of objects for a removal decision and object counting.

The object separation and counting procedure can be summarised as a three-step task: (1) generation of a Vis-NIR classified material image[a] (chemical image), (2) generation of a grey-scaled image and (3) performing a superposed digital image processing.

Spectral imaging and material classification

Spectral imaging represents a fusion of imaging and spectroscopy. It is based on intensity distributions of photon fluxes over a contiguous range of narrow spectral bands from all organic material surface pixels in a spatial scanned line. The intensity distributions of photon fluxes result from overtone or combination bands of molecular vibrations with related frequency-dependent energy absorption. The rejected light of each pixel along the scanned line of a sample needs to be spectrally dispersed to give a two-dimensional image that is projected onto a two-dimensional sensor array.[3] For the “N²IR”-system, the dispersion is performed by a diffraction grating.

The conventional NIR wavelength range for plastics sorting in the recycling branch is 900–1700 nm. InGaAs semiconductor sensor arrays are state-of-the-art for NIR spectral imaging in this wavelength domain. The main reason is that all practically relevant kinds of plastics feature characteristic overtones and/or combinations of spectral bands in the 900–1700 nm range, i.e. in the most sensitive range of well-adjusted InGaAs alloys. But characteristic features can also be found in the third overtone region (750–980 nm). The advantages of the Vis-NIR spectral imaging region consist in the possibility of employing less expensive CMOS-arrays as light sensors.

By measuring the Vis-NIR light (spectra) that is emitted from a surface point of a sample it is possible to assess its chemical composition. This allows the identification of items regarding the material they are made of. Nevertheless, the identification and classification procedures are not simple tasks. There are two different approaches for spectra classification -,feature extraction,[4] multivariate regression methods[5] or a combination of both. Feature extraction is used for classification purposes when the spectra of the materials to be sorted show slightly distinguishable shape characteristics in different spectral ranges. That is applied to the raw spectra as well as the so-called derivative spectra. Feature extraction is the fastest way to distinguish the most relevant kinds of domestic plastics like polyethylene (PE), polypropylene (PP), polystyrene (PS), PET and polyvinyl chloride (PVC) in the 900–1700 nm spectral range.

If the spectra of different kinds of organic materials are not decisively discriminatory concerning shape characteristics, feature extraction is hardly applicable. For example, this occurs with ABS and PS discrimination or when using NIR spectroscopy for quantitative analysis. In such a situation, multivariate regression is the method of choice for classification assessment. Due to the fact that NIR spectra are generally highly correlated, principal component analysis (PCA) and partial least squares (PLS) regression are successfully applied to predict the composition of organic materials or blends. The “N²IR”-system uses PLS methods for PET identification, although simple feature extraction methods or logistic regression would likewise fulfil the task. There are no relevant differences in computing time but the PLS routines are more efficient in other applications than PET-sorting in RVMs.

Object segmentation and counting

The material classification leads to a pixel matrix (chemical image) in which the different materials are marked. The next step of processing is object segmentation[6, 7], to separate items for counting and building up the so-called valve mirror of a pneumatic sorting machine. Depending on the application, there are diverse demands. Centre of gravity is the most important property for sorting flakes of smaller size while, when sorting whole items like PET-bottles by RVMs, many more properties of an object are significant. In particular, the exact outline and boundaries of bottles need to be identified in order to count accurately.

The accuracy of segmentation algorithms depends on the resolution of the sensor over the conveyor belt of a sorting machine. In contrast, the signal-to-noise ratio is improved by averaging the spectra over the belt. A common solution for this optimisation problem is the fusion of NIR spectroscopy with a high resolution VIS sensor system where synchronisation of both sensors is the main task; heterogeneous moving objects especially can cause instabilities. To avoid this problem integrated systems have been developed, as described by Balthasar and Rehrmann.[8] The information is acquired physically at the same time at the same

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[a] For parameter development of the NIR-classification models the statistical software tool “DataLab” from Epina GmbH, Austria, was chosen.

place. This concept is the optimal solution for smaller flakes but for the sorting of whole items another approach is to interpret the raw information of the spectrometer as a grey-scaled image. Therefore, the whole spectrum is averaged to one intensity value for a surface pixel. This is done with the full resolution of the sensor over the complete conveyor which yields an image of a row. By moving the conveyor and fusing the row-images, a two-dimensional image is built up. As a result, it is possible to collate two different sources of information from one sensor at the same time. At this point the grey-scaled image can be used for the object segmentation in combination with the material information. In contrast to a two sensor solution, the grey-scaled image has a comparable resolution over the belt but a much smaller one over the moving direction of the conveyor. Since the spectral information is based on reflective analysis it is not possible to receive real colour information of an object but for counting purposes the colour does not play any role. The entire operational sequence of the data processing chain is represented in Figure 2.

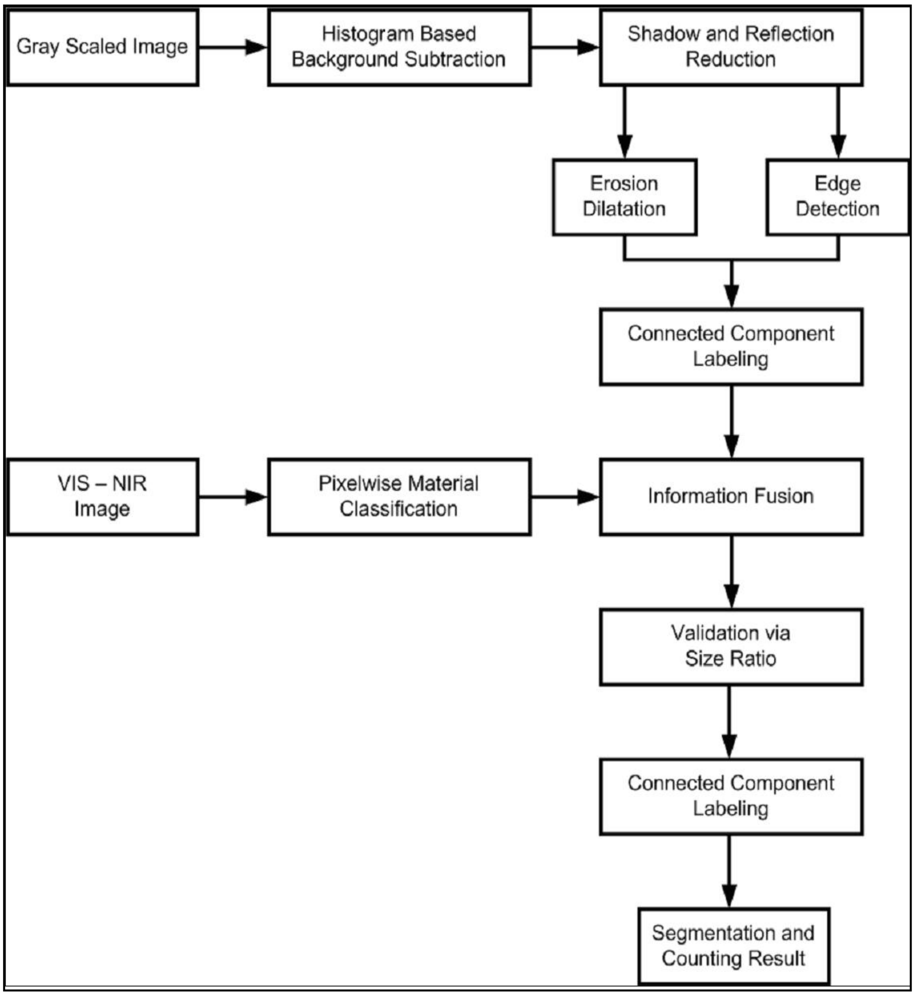

Figure 2. Entire operational sequence of the data processing chain.

Results and Discussion

Material classification

Figure 3 shows smoothed second derivative reference spectra for PET, PE and PS, respectively. The spectra were measured in reflectance mode. The derivative spectra distributions clearly show that there are a lot of discriminative characteristics for the different kinds of plastics. Typical minima and maxima in the second derivative spectra can be chosen for a very fast automated identification of the origins of the spectra.

For assessment of the sorting performance, an experiment similar to that of Hollstein *et al*.[1] has been performed using the sensor module developed: 25 kg of pre-sorted plastic flakes (80 % PET, 20 % mixture of PE, PP, PS and PVC, flake dimension 1 cm^2) were sorted in a negative mode (blowing out waste) to increase the PET concentration. Quality criteria in such experiments are the sorting accuracy in the resulting PET-fraction and sorting accuracy of the not intended PET-percentage in the mixture fraction. As a result of 10 independent experiments the following values have been achieved: PET concentration in the PET fraction was 97% ± 1.5%; PET concentration in the mixed fraction was 6% ± 2%. The experiment was a preliminary investigation to ensure a correct material classification procedure of the “N^2IR”-system.

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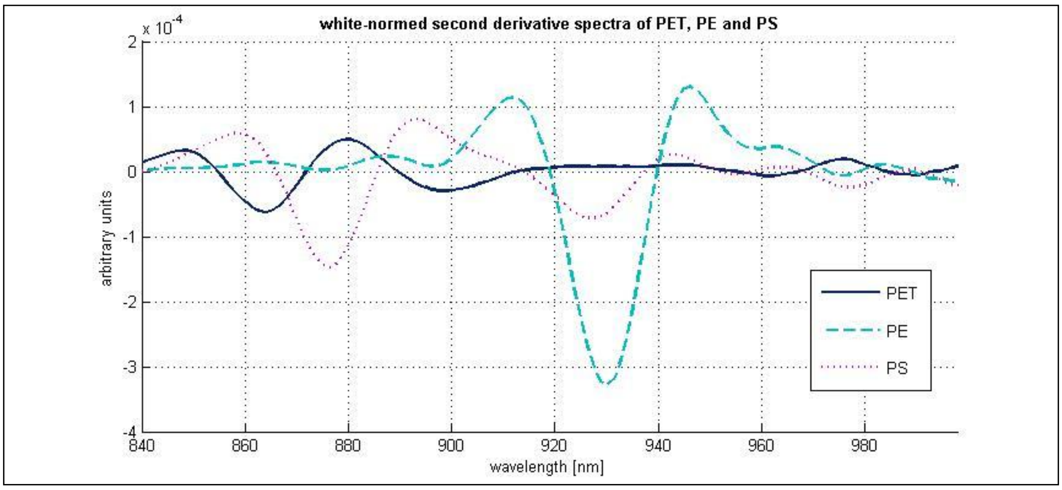
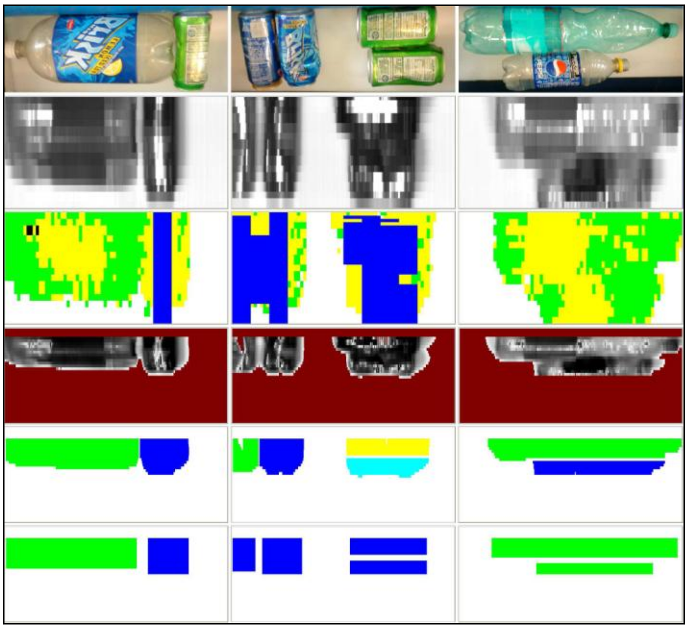


Figure 3. Second-derivative spectra of PET, PE and PS in the range of 840–980 nm.

Object counting

For testing the object segmentation based on grey-scaled imaging, a new[9] high throughput RVM was used (www.reimaginerecycling.com). It is an ascending conveyor with a belt velocity of 1 m s^{-1}. One demand on this particular machine is the sorting of up to 100 items per minute. The sensor is the “N²IR”-spectral imaging system with direct access to the raw data. The sample rate was adjusted to about 50 Hz. In the material input stream, all kinds of plastic bottles and aluminium cans could occur. The purpose of the machine is to separate PET and aluminium from non-PET (PE, PVC, PP) and non-aluminium items. Aluminium has been detected by an additional metal sensor. Due to the high throughput, many items touch directly and for correct separation and counting, such complicated situations must be treated effectively.



original pictures

grey-scaled pictures

chemical images

digital processed grey-scaled images by taking into account chemical composition

component labelled pictures

valve mirrors of RVM

Figure 4. Process chain from original picture to valve mirror.

In Figure 4 some typical scenarios are shown. In the left column, a PET-bottle is touching a standing aluminium can; in the middle, two cans are standing, two lie close to each other while in the last column two PET-bottles are touching. The first row shows the RGB-pictures of the cases. In the second row the grey-scaled images are presented. These consist of 720 pixels in the x-direction. Each image represents 40 row-images in the moving direction of the conveyor. In the third row the corresponding material images of the test cases are shown. Green holds for PET, yellow for non-PET-plastics and blue for aluminium. The aluminium information is received from an additional metal sensor under the conveyor belt. These “ALU-pictures” have a resolution of 72 pixels over the belt. The boundaries between items appear much clearer in the grey-scaled image than in the material image which is the basis for future processing. The next row shows the re-

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sults of the background extraction based on the cumulative histogram with the removal of reflections and shadows for the grey-scaled images; duplicate rows were also removed. The fifth row presents the results of the border processing and connected component labelling whereby the different items have been labelled by different colours. The last row shows the resulting valve mirror for blowing out the detected PET or aluminium items by the sorting machine. The different colours correspond with the material as in row 3. With the shown algorithm, the accuracy of correct separating and counting reached 98% (every second item was touching, and a maximum of 5 items touched in one image). The sample time of the algorithm (implemented in C++) depends on the number of objects but is less than 20 ms. Consequently the applicability for RVMs has been demonstrated.

Conclusion

To discriminate PET bottles from other impurities in the input stream of a reverse vending machine a new highly efficient material selective sensor system ("N²IR") based on spectral imaging and digital image processing in the 750–980 nm wavelength range has been described. The Vis-NIR spectral imaging system fulfils all requirements for PET bottle recognition and impurity removal in advanced RVMs. The sorting productivity based on hyperspectral imaging is higher by a factor of 10 when compared with other known online systems for such kinds of machines.

Acknowledgements

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