A new cost-efficient high-speed vis-near infrared spectral imaging system for online sorting of plastic waste

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Introduction

Waste recycling is not only an essential environmental protection demand but also an important source for raw materials saving. Especially plastic-, electronic-waste- and paper-recycling are growing business areas. In the field of sensor-based automated sorting and separation the first NIR spectral imaging systems have entered the market. The process is driven by enormously accelerated developmental periods in the electronic hard- and software sectors. However, the main decelerating elements for the recycling industry today are still the severe costs for the sensor systems. From this point of view a new cost-efficient high-speed vis-NIR spectral imaging system for online sorting of plastic waste has been developed to meet all of the requirements for an automated sorting operation at the industrial level.

The conventional NIR wavelength range for plastics sorting according to recycling purposes is 1.000 . . . 2.100 nm. Expensive InGaAs semiconductor sensor arrays are the state of the art for NIR spectral imaging in this wavelength domain. The main reason is that most of the dominant household/industrial waste plastics like PE-LD, PE-HD, PP, PS, PET and PVC feature characteristic first and/or second order spectral bands in the 1.000 . . . 2.100 nm range, i.e. in the most sensitive range of well-adjusted InGaAs alloys.[1–3] Characteristic features can also be found in the third overtone region. The intensity values, although an order of magnitude lower compared to first/second order bands, are still high enough for robust detection with appropriate CMOS semiconductor arrays. The advantages of CMOS-arrays compared to InGaAs-arrays are manifold. The detectors have a wide performance range, and are cheaper, and more readily available. In this paper the basic layout of a complete CMOS-based vis-NIR spectral imaging line camera regarding to above mentioned sorting/recycling applications will be discussed. The considered wavelength domain is 700 . . . 950 nm in steps of one nanometer. In the spatial axis a detector with a resolution maximum of 1024 pixels has been chosen. The detection frequency for the spatial pixels with reduced spectral resolution of about 80–100 pixels should be around 400 Hz. To fulfil this requirement contemporary possibilities in spectrometer architecture, sensor electronics design, data processing and hardware-/software performance have been considered.

Table 1. Short specification of vis-NIR-System.

Transmission imaging	object lens f = 8 mm, MegaPixel cmount
Spectrometer	input slit 80 µm
	input filter < 700 nm
	volume-phase holographic (VPH) grating
Wavelength range:	700–950 nm
Intensity digits	10 bit
Semiconductor sensor:	1-MegaPixel-CMOS-sensor, SXGA
Computer:	Core2Duo 2.16 GHz
Data transfer:	Gigabit-Ethernet

Materials and methods

Hyperspectral imaging represents a fusion of imaging and spectroscopy. It produces intensity distributions over a contiguous range of narrow spectral bands from all material pixels. Degradation factors for accurate output images are various: radiometric aberrations, due to the sensor and the optics, perturbations due to atmospherical conditions, random noise in the chemical and geometrical compositions of the parts to be spectral imaged, temperature, and other factors. For minimizing all of the degradation factors a very fast and intelligent software code for raw data adjustment and calibration must be integrated in a vis-NIR-Hardware system. The calibration process includes wavelength gauging and detector non-uniformity correction.

Table 1 illustrates the vis-NIR spectral-imaging-system, which consists of an input lens, an input slit, a transmission imaging spectrometer with coupled CMOS-photodiodes-array (1280 × 1024 pixel, SXGA-format), and additional electronic elements.

This part of the vis-NIR-system is called the vis-NIR smart camera. In the full window mode the frame rate is 30 Hz. Increasing the frame rate can be performed by reducing the imaging window size by a factor of 2^n through changing the register settings of the CMOS-sensor, carried out by software (n integer, for example, if $n = 4$, the frame size decreases to 320 × 256, while the frame rate increases to 240 Hz).

For application in the field of online sorting of plastic waste, the vis-NIR smart camera is usually mounted above a conveyor belt. For each measurement point a complete vis-NIR-spectrum (700–950 nm) is recorded. Spectral and spatial resolutions depend on the frame rate as well as the belt velocity and belt width. For typical operation parameters (belt width = 2 m, belt velocity = 2.5 ms^{-1}, frame rate = 240 Hz) the spatial resolution averages less than 1 cm^2. To perform such a spatial resolution the classification frequency for material identification must be high by comparison with the frame rate. For this reason the smart camera is composed in a multi-stack printed circuit board assembly (PCB) with integrated Spartan 3 field programmable gate array (FPGA), see Figure 1.

Pre-processing of spectral data is by Savitzky-Golay smoothing with third polynomial and 15 points convolution intervals. Normalization is performed by min-max-stretching of derivative data-sets. Because of a linear decreasing quantum efficiency of the CMOS-sensor in the consid-

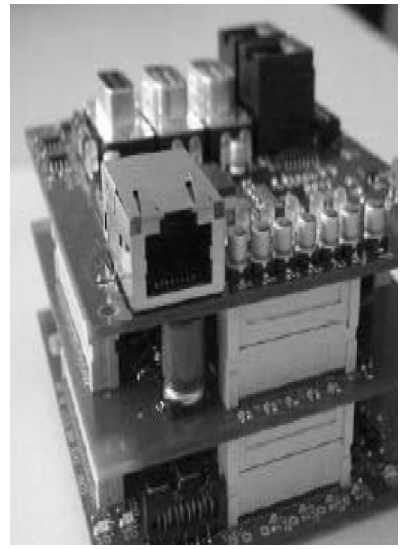

Figure 1. Image of electronic hardware solution composed in multi-stack PCB and FPGA technique.

ered vis-NIR spectral range, special attention has to be paid to assuring a stable white reference. The same applies to the signal-to-noise ratio.

The data which are pre-treated via FPGA, are continuously processed by a Core2Duo-computer. Data transfer for classification of spectra and generating of so called valve mirrors for blowing out desired plastic objects is performed via GigE. One of the two cores is responsible for the data reception, while the other core performs the classification and valve mirror determination. Hence a gap of one frame appears in the valve mirror calculation.

To assess the practical and industrial relevance of the new cost-efficient high-speed vis-NIR spectral imaging system a small sorting module with 1.000 mm belt width and 2 ms^{-1} belt velocity has been used for estimation of sorting accuracy with regards to shredded plastic flakes (PE, PP, PS, PET, PVC). The flake grading was in the range of 1–4 cm^2 and nozzle interspace amounts were 12.5 mm.

Results and discussion

Figure 2 plots second-derivative reference spectra for PET, PP and PS, respectively.

The spectra were measured in reflectance mode, averaged over 30 datasets and min-max normalised. The derivative spectral distributions clearly shows that there are a lot of discrimination 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 practical assessment of the sorting performance a practical experiment has been performed in the recycling branch by using the above-mentioned sorting module: 25 kg of pre-sorted plastic flakes (80 % PET, 20 % mixture of PE, PP, PS and PVC) 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

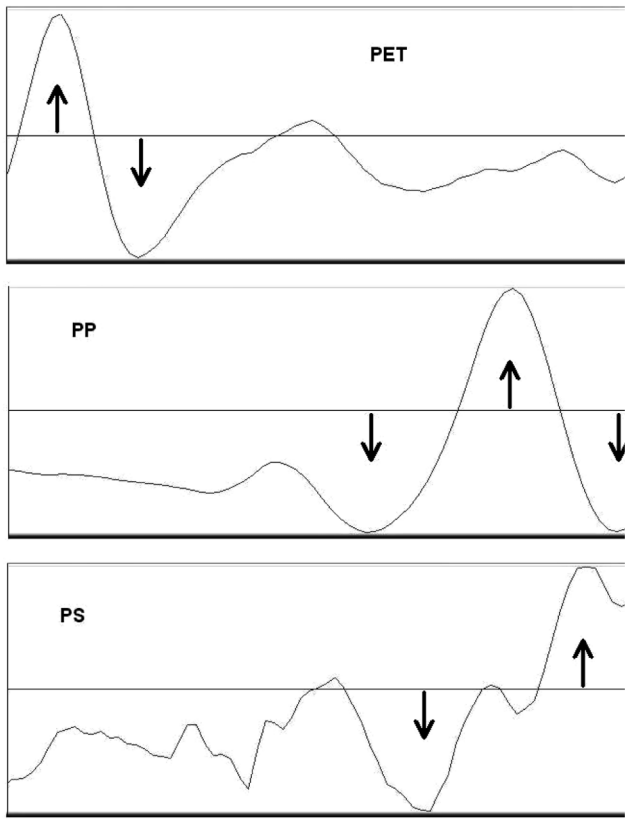

Figure 2. Second-derivative spectra of PET, PP and PS in the range of 700–950 nm, arbitrary units, min-max normalisation.

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 %.

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