Multiplexed NIR spectroscopic Sensors and NIR spectroscopic Imaging: Two Solutions for Sensor based Waste Sorting in Comparison

Arne Volland

LLA Instruments GmbH, Berlin, Germany

Abstract

Different systems for plastic sorting, which utilize multiplexed near infrared (NIR) sensors, have been established in the recycling industry, so far. They offer a high spectral resolution and a high dynamic range (16 Bit), so that even the smallest material differences can be detected. Besides identifying standard polymers like PET, PE, PP, PVC and PS these systems can also solve difficult sorting problems like the recognition of PET-bottles with PVC- or PP-labels. Belt widths of up to 4 meters are possible and colour sensors can be integrated into the optical systems, easily. A limiting factor is only the reduced spatial resolution because of the maximum number 64 tracks (corresponding 31mm pitch at 2m belt width) and the relatively low scan rate of up to 100Hz.

Recently hyperspectral NIR imaging systems, which work without optical multiplexers and handle 256 tracks at scan rates of up to 330Hz, have been developed. However, they have a reduced dynamic range of 12 Bit and detect only the shortwave NIR spectral range up to 1.7µm, which may limit the possible applications. At belt widths of up to 2 meters these new systems can be used for sorting standard plastics as well as plastic flakes >5mm.

The article compares the advantages and limitations of both systems and demonstrates the fields of use on the basis of practice-oriented examples.

Keywords

Plastic, sorting, hyperspectral, multispectral, imaging, near infrared, NIR, sensor

1   Plastic identification with NIR

Because all polymers consist of long chain molecules with recuring molecular groups, nearly all plastic types can be identified by the means of near infrared spectroscopy. If such a material is illuminated by a standard halogen lamp, the infrared radiation enters the sample and is multiply scattered in its interior, where interactions with the material occur. By the absorption of photons the sample molecules are excited to oscillate. A small fraction of photons finally reaches the surface again, is diffusely remitted by the sample and can be analysed by an NIR spectrometer. A quantum mechanical treatment of the molecules shows, that they can only oscillate on certain energy levels, from which follows, that they can only absorb certain photon energies (Figure 1) corresponding to certain wavelengths in the NIR absorption spectrum. Thereby, specific molecular groups

absorb only certain spectral ranges resulting in absorption bands, which are specific for the material composition. Typically, the fundamental mode for the C-H stretch vibration is around 3500nm and the first and second overtones are around 1700nm and 1150nm, respectively (WORKMAN, WEYER). As indicated in Figure 1 with increasing order of the transition the absorption strength decreases and the bands are increasingly broadened. This property is essential when selecting the appropriate wavelength region and sensor for a specific application.
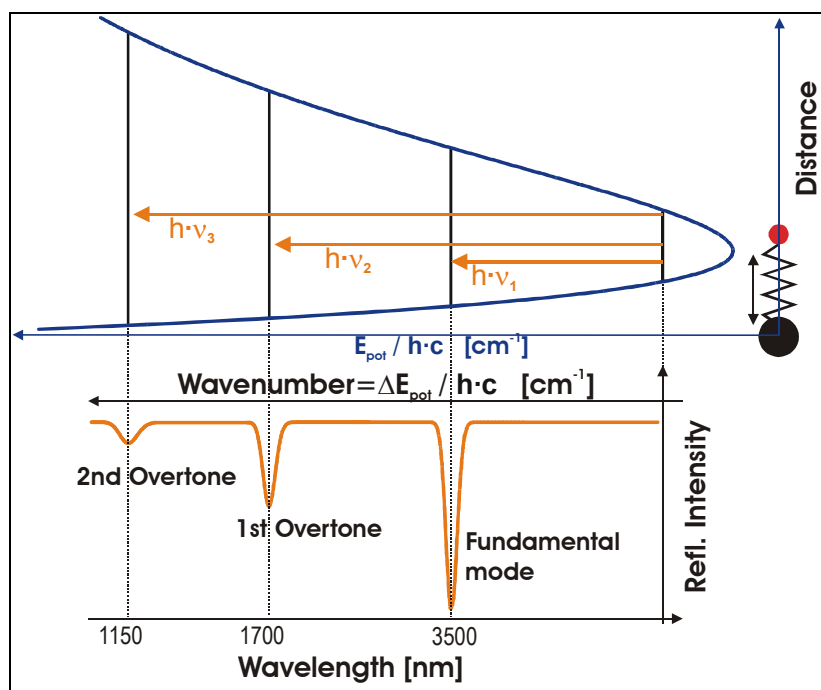

Figure 1: Schematic diagram of the vibrational modes and NIR absorption bands of a diatomic molecule.

Because the penetration depth of NIR radiation (1.1µm-2.0µm) into the standard polymer types can be up to a few millimetres, the plastic identification is widely independent of surface contaminations. Even labels made of other polymers can be penetrated, so that the material beneath can be detected, which is subject of the following.

2   NIR-sensors

The two devices under comparison are a Kusta 4004M multiplexed NIR spectrometer (MPL) and a KustaMSI 1.7 multispectral imaging (MSI) spectrometer from LLA Instruments, where the latter is based on the Helios 1.7 device from EVK DI Kerschhaggl. Both systems work with the well-established chemometric analysis routines (PLS, PCR, Neuronal Networks etc.) used so far as standard for identification with the Kusta 4004M multiplexers. This makes a direct comparison of the identification performance possible. Figure 3 illustrates the covered spectral regions of the MSI- and MPL-sensor on the basis of four spectra of the most common polymers.
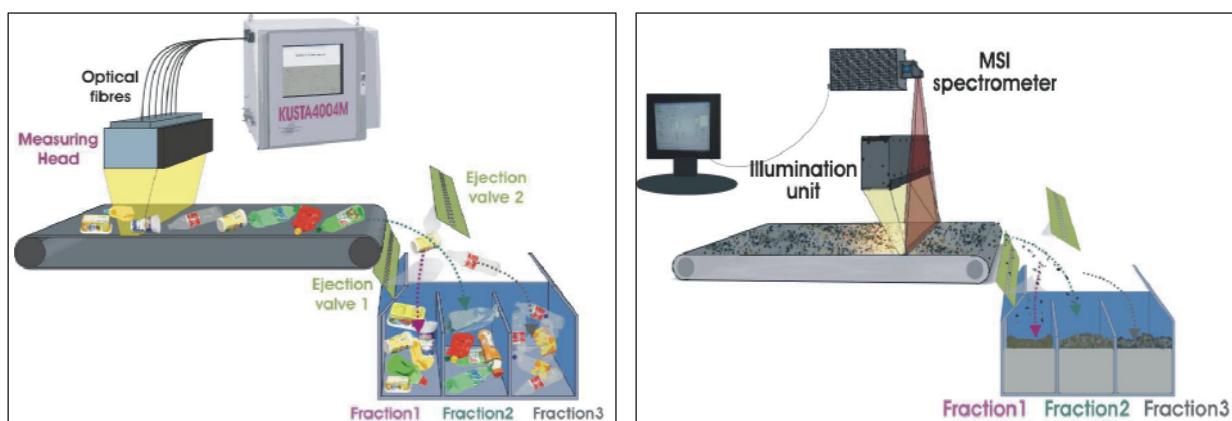
Figure 2: Schematic setup of the MPL system (left) and the MSI system (right).

Because the important 1st overtone vibrations of PVC and the Polyolefines (PE, PP), which are very strong and equipped with many details in shape, are not accessible to the MSI-sensor, the chemometric identification routines have to be trained mainly on the basis of the weaker and broader 2nd overtone vibrations. In contrast to that, the MPL-sensor covers the complete 1st overtone region, which makes the identification more sensitive and reliable.
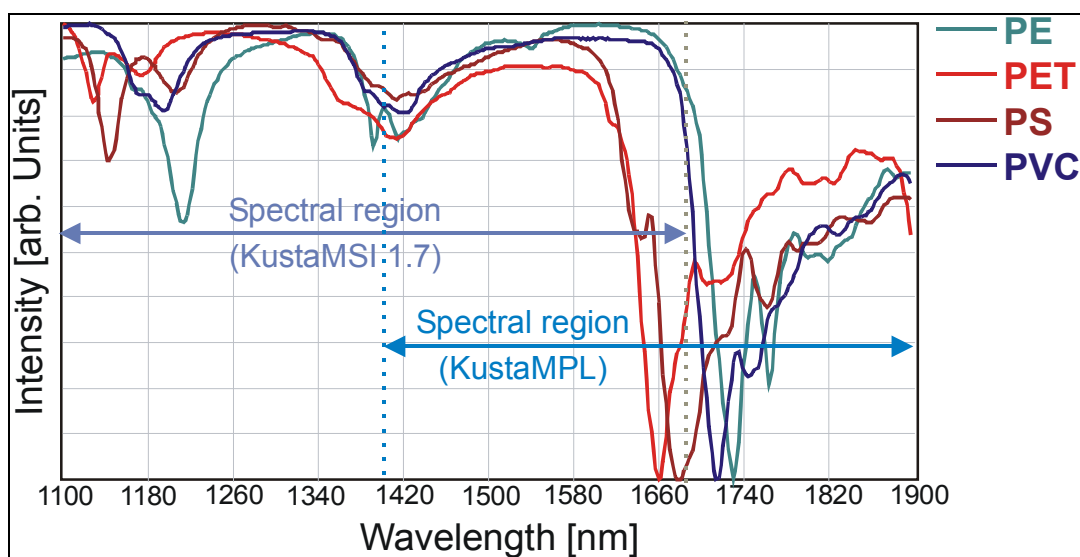

Figure 3: Spectral regions of KustaMSI and KustaMPL for spectra of common polymers.

3   Identification of PET-bottles with different plastic labels

In the recycling of household waste one of the most important sorting tasks is to recover polyethylene terephthalate (PET bottles). Typically they are labelled with printed foils of other polymers, where PP, PS, PVC, PE and paper are common. Depending on the process conditions and the demands of the final product, it may be of interest to sort out PET bottles with PVC-label. Especially for bottle-to-bottle recycling this is necessary, because during injection molding of PET (~280°C) the presence of PVC contaminations

leads to the formation of HCl-gas, which destroys the polymer chains of the PET and leads to impurities in the recycled product. In contrast to that, when down-recycling to a product of lower quality, it will be of interest to recover as much PET as possible independent of the label.

In the following, this application is chosen for a comparison between the identification performance of the MPL- and the MSI-system. While both systems identify pure polymers with high accuracy, the evaluation of mixed-spectra, as they occur in the case described above, is a more demanding task. The test measurements were performed on a laboratory plant under the following conditions:

Table 1: Measuring conditions of the laboratory plant and theoretical values for MSI (grey)

	MPL	MSI	MSI (2m)
Belt speed	1.6m/s	1.6m/s	1.6m/s
Frame rate / scan frequency	50Hz	240Hz	240Hz
Resulting measurement distance in moving direction	32mm	6.7mm	17mm
Track pitch (perpendicular to moving direction)	32mm	3.1mm	8.3mm
Corresponding maximum belt width for 64 tracks (MPL) and 240 tracks (MSI)	2000mm	750mm	2000mm

In contrast to the MPL-system the track pitch is not variable for the MSI-system but depends on the used objective (f=8mm) and measuring distance. Because on the laboratory plant a belt width of 2000mm was not attainable with the available optics, the spatial resolution of the MSI-system is higher than it would have been under comparable conditions. For each type several hundred of spectra were recorded, on labelled and unlabeled parts of different plastic bottles. Subsequently, a partial least squares algorithm (PLS) was trained with the data, where it carefully was kept track of using exactly the same samples for the training of both systems. From the scores plots of the two methods (Figure 4) it can be seen that KustaMPL reaches a good separation between the three types, while PET+PVC and pure PET overlap slightly on KustaMSI. This effect is assumed to be due to the short wave NIR region covered by the MSI-sensor, where the important 1st overtone absorption bands of PVC (1.717μm) cannot be detected. A few of the PP-labels showed strong reflections leading to a large spread in the point clouds of PET+PP, where the MSI-system seems to be more sensitive to this effect. This can also be observed in the processed image of the bottles on the moving conveyor belt (Figure 5). At the MSI record two of the PP-labelled bottles have missing identification points on the label (light grey) indicating that these spectra could not be evaluated because of strong reflections.
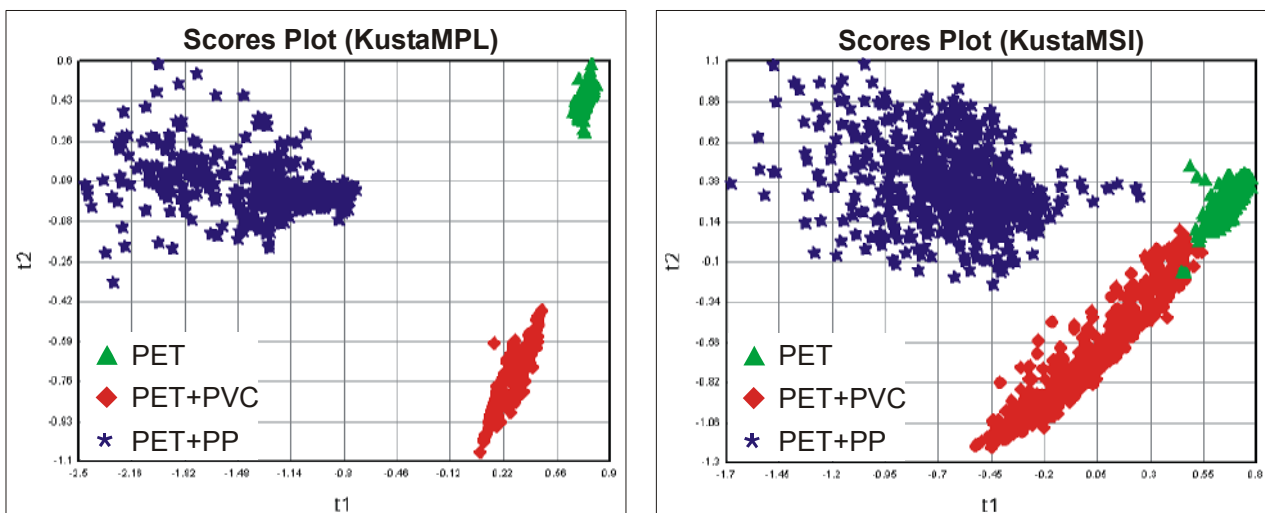
Figure 4: Scores plot of a PLS routine trained on PET bottles without label and with PVC- or PP-label for KustaMPL and KustaMSI.
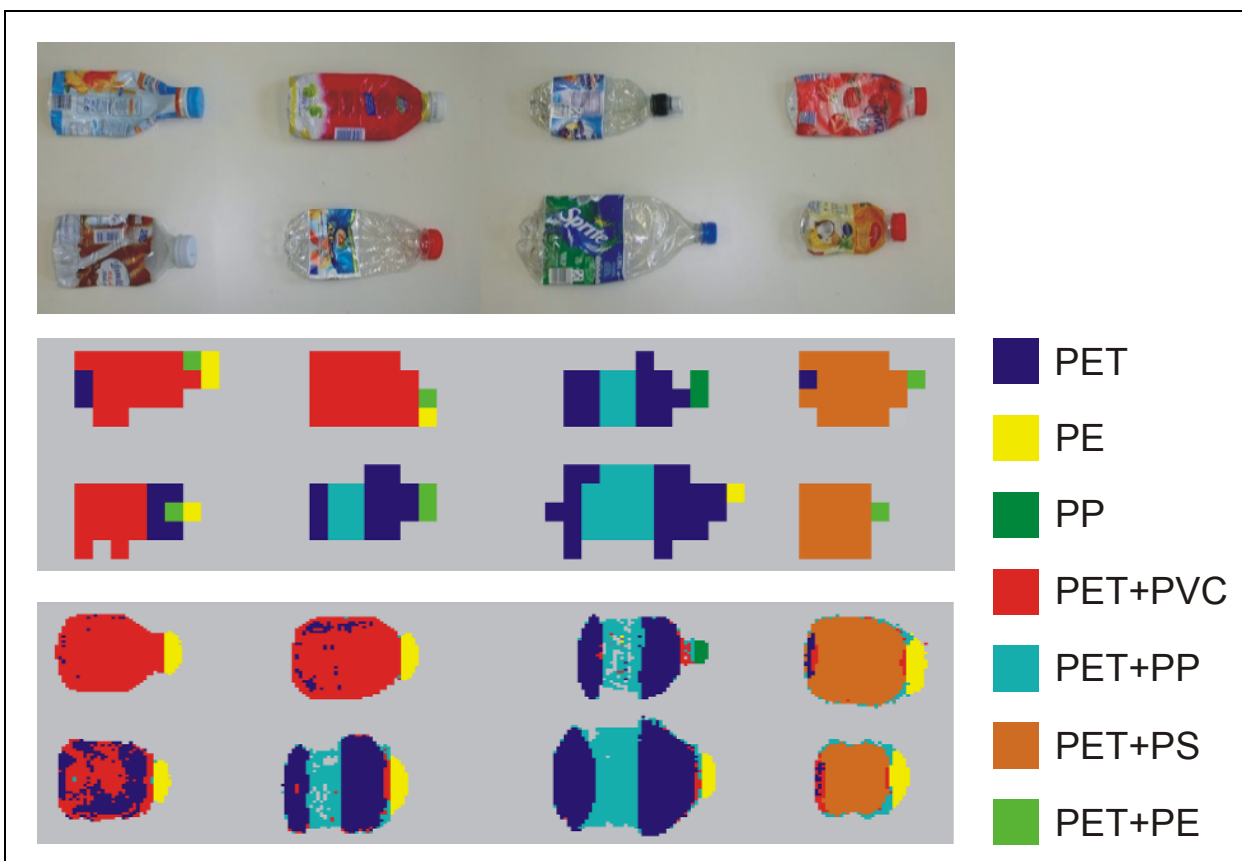

Figure 5: Process image (NIR identification) of PET bottles with different plastic labels and PE or PP-caps for KustaMPL (top) and KustaMSI (bottom). PVC- and PS-labels covered the complete bottle.

The MPL-system does not show this behaviour, because it averages over a larger measuring area ($\varnothing$=32mm) and has a higher dynamic range (16bit). Remarkable is also, that the PE- or PP-caps are identified correctly not only by the MSI-system but also by the MPL-system, at least as mixed spectra PET+PE.

While the MSI-system identifies all samples correctly as PET bottles, the classification of the mixed spectra from the labels is ambiguous and shows some mixing between PET+PP and PET+PVC. This indicates that although pure plastics can be identified well with KustaMSI, the analysis of mixed spectra is limited in this application.

4   Combined NIR- and colour recognition with KustaMPL

Due to the modular setup, which combines an optical multiplexer with an NIR spectrometer, a colour sensor (RGB) can easily be integrated into the MPL devices. Figure 6 illustrates the principle of function: The multiplexer sequentially images each fibre cable (track of the measuring head) via a rotating mirror onto the entrance slit of the NIR spectrometer. Between both units a dichroic mirror couples out the visible range of the light and focuses it onto the RGB-sensor, while the near-infrared part passes unhindered to the spectrometer.
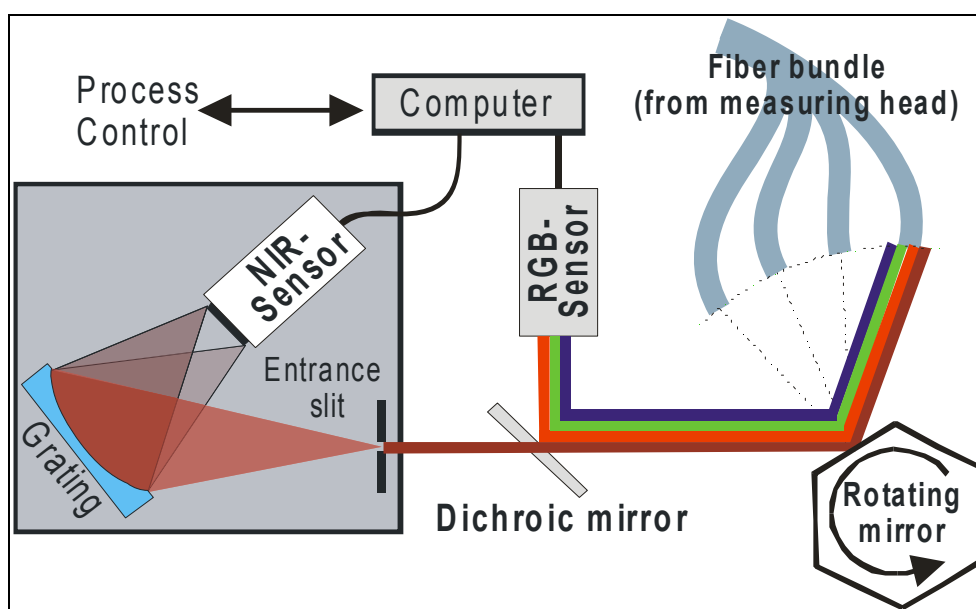

Figure 6: Schematic layout of the KustaMPL system with integrated RGB-sensor.

In contrast to other systems combining NIR- and RGB-sensors the present layout guaranties that both signals are detected exactly at the same time and the same position on the sample. The data is evaluated in a computer, where a PCR or PLS algorithm analyses the NIR spectrum as before, while the RGB data is converted into the HSV space (Hue, Saturation, Value). Because the hue parameter is a compact representation of the colour value and falls in the range 0° to 360° ("colour wheel"), the interpretation and definition of limits for the classes of interest is easy.

Below, the advantage of an additional colour sensor is shown for the application of sorting recycled paper. Because the absorption bands of cellulose and lignin (1600nm-1800nm) have to be evaluated, this sorting task can only be treated with an MPL sys-

tem. The data was recorded in a recycling plant under process conditions (belt width 2.4m, belt speed 2m/s). In paper production even small fractions of cardboard reduce the brightness and lead to impurities in the final product, so that one important sorting task is to separate corrugated cardboard from newspapers and office papers. With the recorded spectra a PLS algorithm was trained, where the corresponding scores plot is shown in Figure 7. Obviously, the three types overlap slightly in the PLS scores space as well as in the HSV space. Because of that, neither sensor is capable of separating the three types alone. Especially the deinking loss of 10.5% (Table 2) is too high, when using only a single NIR identification. But with the following combination of the NIR- and RGB-results, the separation accuracy increases significantly:

- A measurement is classified as "CC", when the NIR- *and* RGB- result is CC.

- When the NIR-result is "OP" and the RGB-result is "CC", the measurement is re-routed to "CC" (this is possible, because there is no overlap between OP and CC in the HSV space)
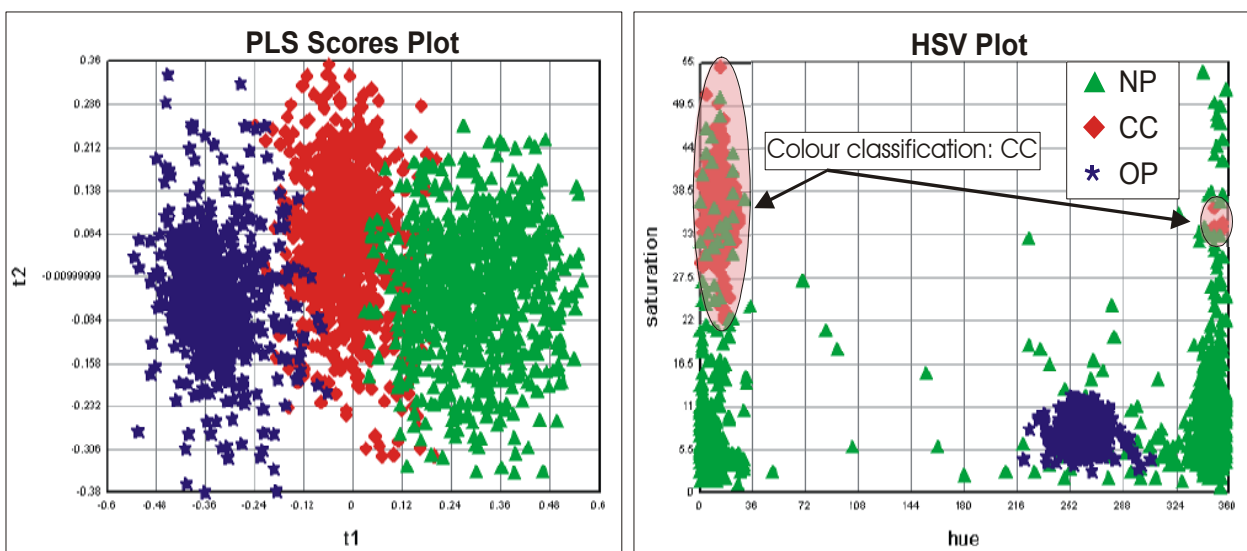

Figure 7: PLS scores plot and HSV plot for the separation of corrugated cardboard (CC), newspaper (NP) and office paper (OP).

Table 2: Classification results for the separation of CC, NP and OP.

	only NIR (without RGB-sensor) [%]	only RGB (without NIR-sensor) [%]	NIR- combined with RGB-sensor [%]
CC classified correctly	93.6	100	95.5
CC misclassified as OP	1.9	0	0
NP misclassified as CC	5.7	3.9	0
OP misclassified as CC	4.8	0	0

With this logical link the deinking loss (NP and OP misclassified as CC) is eliminated, while 1.9% of CC misclassified as OP is retrieved as CC.

5   Sorting of shreddered electronic waste (WEEE) with KustaMSI

The following investigation was performed with the KustaMSI system on the same laboratory plant and under the same measuring conditions described in section 3 (240Hz frame rate, 750mm measuring width). A multistage identification tree was developed, in which five different PLS methods were linked together to identify all important polymers occurring in shreddered electronic waste. The included plastic types were: ABS, PS, PA, PBT, PC, PE, PE, PMMA, POM, PP, PPE+SB, PUR and PVC.

To test the identification accuracy and the spatial resolution, different plastic particles of size <8mm were aligned in a regular grid of 20mm spacing. The test pattern was measured at a belt speed of 1.6m/s. In this application the high spatial resolution and frame rate of the MSI-system are essential. The processed NIR-image of the samples on the conveyor belt shows, that the particles are identified correctly and can clearly be separated from each other (Figure 8). Even ABS and PS, which have very similar NIR spectra due to their related chemical composition, are classified correctly. However, from Figure 8 it can be seen that the spatial resolution perpendicular to the moving direction is better than the resolution parallel to it. Most samples have a long drawn-out shape in the process image. Unfortunately, this effect is unavoidable because of the long integration time necessary for the MSI-sensor (~3ms). At a belt speed of 1.6m/s each particle moves 4.8mm during that time, what tends to "blur" the particles in moving direction.
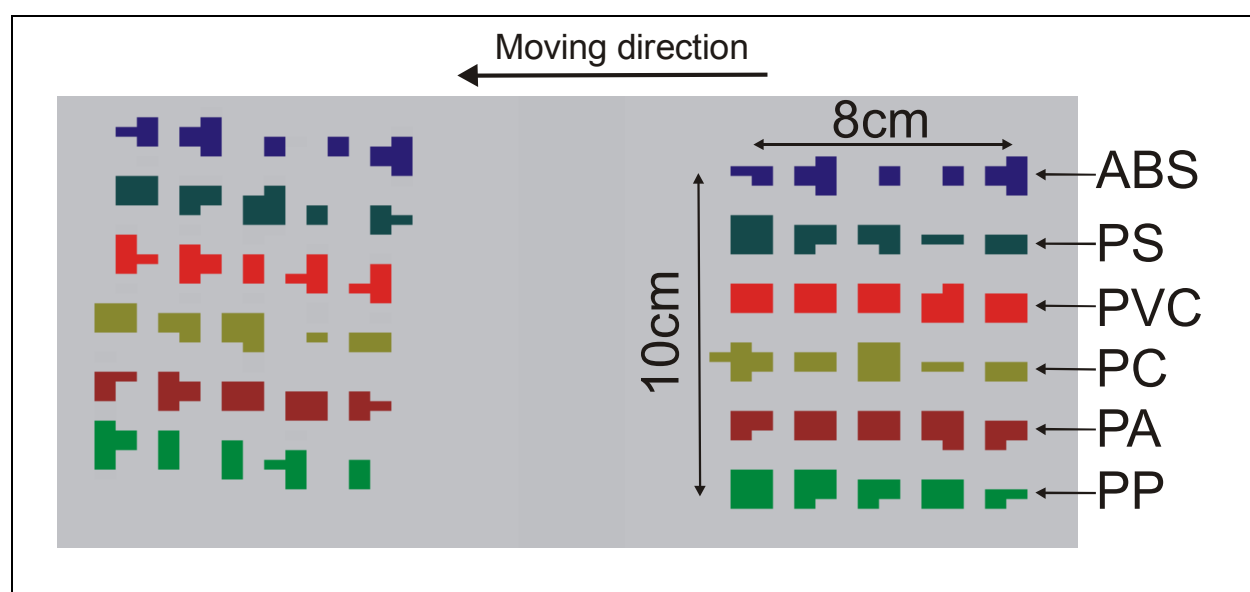

Figure 8: Shreddered plastic flakes (size 6-8mm) recorded with KustaMSI 1.7.

6   Conclusion and prospects

The spatial resolution of the multiplexed NIR system (KustaMPL) has been shown to be absolutely sufficient for sorting household waste and recycling plastics. Especially applications, where mixed spectra have to be evaluated, can better be treated with the MPL system. Here, the longer wavelength region covered and the higher dynamic range is necessary. The usage of fibre optics opens up the possibility to connect one device to different conveyor belts (master-slave configurations), so that up to four plastic types can be separated by one MPL system.

For the sorting of shredded plastics with particle sizes <20mm the KustaMSI system is better suited, due to its high spatial resolution and frame rate. Because it is capable to separate even 6mm small particles, it is especially appropriate for the sorting of WEEE- and PET-flakes. Larger belt widths of up to 2m will be accessible to the MSI-system in the future by using folding mirror optics. Special NIR objectives are tested, to further increase the sensitivity and resolution.

References:

Jerry Workman, Lois Weyer   2007   "Practical Guide to Interpretive Near-Infrared Spectroscopy", CRC Press.

Author's address:

Dipl. Phys. Arne Volland
LLA Instruments GmbH
Justus-von-Liebig Str. 9
D-12489 Berlin
Phone: +49 30 6290790-0
Website: www.LLA.de