

Innovative Technologies as Enabler for Sorting of Black Plastics

Dirk NÜBLER¹, Robin GRUNA², Christian BRANDT³ Andries KÜTER¹, Thomas LÄNGLE², Michael KIENINGER³, Nils POHL¹ ¹ Fraunhofer FHR, Wachtberg, Germany ² Fraunhofer IOSB, Karlsruhe, Germany ³ Fraunhofer IAIS, St. Augustin, Germany Contact e-mail: dirk.nuessler@fhr.fraunhofer.de

Abstract. Thermal recycling of plastics is no longer seasonable. More modern recycling techniques require pure fractions containing only a single variety of polymer. A large portion of the plastic waste contains black or multilayer materials that are not sortable with todays' sorting technologies. A number of means to analyse and sort mixed plastic waste based on the specific mechanical, electrical, and chemical properties of its components such as density, conductivity and melting point have been developed. The most promising electromagnetic principles like X-Ray imaging employs ionizing radiation that requires special safety measures, while infrared and visible light is absorbed by the carbon in black plastics. Publications in the last few years show the feasibility of identifying and then separating different types of plastics based on their specific frequency response in the millimetre-wave and terahertz region. From an economical point of view, a line camera radar system operating between 30 GHz and 300 GHz offers an acceptable trade-off between cost, resolution and enough information to reliably identify different materials. The system approach uses data-driven statistical machine-learning methods for classification. The use of deep neural networks in combination with very large training-datasets with thousands of samples improves the predicted sorting purity between 90% and 99.9% for common use-cases. Finally the THz-camera and the classification methods have to be integrated in a sorting solution that meets the realtime requirements of recycling systems. Due to the modular approach, it is also possible to upgrade existing sorting systems.

Keywords: sorting, recycling, black plastic, line camera, THz

1. Introduction

High frequency sensors allow a view inside the most non-conducting materials and products. With a typical wavelength between 10 cm and 1 mm the resolution is limited by the chosen frequency range. The dynamic range of a high frequency system can be limited by many factors. E.g. an A/D converter can decrease the dynamic range despite the dynamic range of the system is much higher. Line cameras can be realized in transmission and reflection configuration and are separated in continuous wave (cw) systems and systems which offer a range resolution, like frequency-modulated (FMCW) or pulsed signal concepts. For the system approach a stepped frequency method (SFM) was chosen. It offers the best trade-off between a low power sensor and high resolution concept. A wide



spectrum of several frequencies can be used. In recycling applications sorting machines for plastic uses hyperspectral cameras which measure only the attenuation of the reflected signal. These optical sensors are not able to sort black plastics, due to the reflected light from the black surfaces is too low for a stable detection process.

Publications in the last years demonstrate the possibility to separate different plastics through their frequency response in the lower THz region [1]. These systems offer the possibility to measure the dielectric properties of non-conducting materials. Photonic THz spectrometers offer the possibility to sweep over a large frequency range in a few milliseconds. Unfortunately, these systems are expensive and to slow for line arrays in a production line with a typical belt speed of 3 m/s. THz Systems based on cheap frequency multipliers are faster but they are working with a smaller frequency range. They could be used for industrial issues if the range is sufficient. From a more economic point of view the best compromise between costs and resolution can be realized in mm-wave band between 30 GHz and 300 GHz.

In the frequency range above 2 THz solid state materials have characteristic absorption lines which can be identified by a recognition algorithm. Without absorption lines a standard finger print analysis is not possible. The change of the dielectric properties over the frequency range is another approach to visualize the differences in the materials. Unfortunately real materials show a large diversity due to additives like plasticizers, flame retardants and UV resistance. In a first approach, methods based on Gaussian Mixture Models (GMM) and a Universal Background Model (UBM) was used. Using the Hilbert envelope of various band-filters, the amplitude and the time-position of the signal peak was extracted as features for a GMM-UBM system. To choose the optimum frequency range, the selected machine learning algorithms were trained with test data sets (Fig. 1). In a second step a blind test was performed. The lowest frequency range with sufficient results was the W-Band from 75 GHz up to 110 GHz. With a limited number of classes, test sets and a first prototype algorithm a probability between 85% and 90% for identification were realized. Based on these results a decision was made to realize a first test system in the lower THz region [2].



Fig. 1: Measured attenuation for pieces of plastic for different frequencies in the lower THz region

2. Sensor concept

The blackValue® system is a multichannel line scan THz camera based on commercial off the shelf (COTS) components. For the main system reference, a 1 GHz SAW-based crystal oscillator (XO) with a very low phase noise of -138 dBc/Hz at 10 kHz offset is used off of which phase aligned DDS references at 1 GHz and ADC sample clocks at 50 MHz are derived in a phase aligned manner to ensure a completely coherent measurement. While

multiple other measurement modes like single frequency continuous wave (CW) or frequency modulated CW (FMCW) can be realized using out system, a stepped frequency CW (SFCW) operation provides the benefit of a wide bandwidth chirp with arbitrarily spaced frequency steps without concern for frequency ramp linearity. Additionally, when using SFCW a fixed intermediate frequency (IF) that is independent of the distance between transmitter and receiver can be generated.

Transmit and receive signals are generated using two synchronized AD9910 DDSs to achieve chirp to chirp phase alignment. The baseband frequency used ranges from 160 MHz to 320 MHz which is in turn up-converted to a distribution frequency chirp of 1160 MHz to 1320 MHz, again using the master reference for coherency. As we require a measurement signal at an intermediate frequency, the transmitter DDS generates a signal with a frequency offset of 27.77 kHz with respect to the receiver DDS frequency. These two signals are distributed to the transmitter and receiver frontends, respectively (Fig. 2). Inside these frontends, the signals are first multiplied by 24 to obtain a bandwidth of 4 GHz at a center frequency of 30 GHz. In case of the transmitter, the signal is then distributed to 2 legs, each consisting of 4 paths that are selectable via a single pole quadruple throw (SP4T) mm-wave switch. In each of those 4 paths, the signal is tripled again to reach the final working frequency band around 90 GHz with a bandwidth of 12 GHz. Compared to using a W-band SP4T switch that was also evaluated, this approach requires four times the number of frequency triplers, W-band mixers and amplifiers, but exhibits a significantly higher channel isolation of 35 dB instead of 20 dB. As the system is intended to be used in a time multiplexed (TDM) fashion to reduce crosstalk on the receiver aperture, we consider this well worth the increased BOM cost.



Fig. 2: System concept of the line camera for 90 GHz

The receiver is designed in a similar fashion. The distribution signal is multiplied by 24 and then split up into 8 tripler channels. In addition to the transmitter module, the receiver signal path contains an additional amplifier for the received signal. Both the generated and the received signal are fed into a quadrature mixer that down-converts them to an IF of 2 MHz. With an IF lower than 500 kHz, the mixer exhibits low frequency artefacts while at frequencies above 10 MHz it becomes increasingly complex to design sufficiently narrow antialiasing filters (AAF) to meet the Nyquist criterion of 12.5 MHz upper band limit. The 16 IF signals for each of the 8 quadrature channels are then filtered and digitized using two

8 channel 14 Bit ADCs running at 25 MSamples/s in the backend. The sampled data is then processed by a Xilinx Spartan 6 FPGA. First, data corresponding to the currently illuminated receiver channel is selected based on the switch position in the transmitter. As we only measure signal attenuation and phase offset relative to a reference measurement without any plastic flakes in the measurement path, the FPGA proceeds to select one in-phase and one quadrature sample per frequency step. Timing is essential, since a sample taken too early might not be representative as some filter and multiplier stages may still have to settle. Adding a large safety margin is not ideal either as this directly translates to a longer measurement period and thus an elongated measurement spot on the flake to be analysed. Following the sample selection stage the data is encapsulated into UDP packets and transmitted via a dedicated Ethernet connection.

To connect more than 8 channels to the image processor and to provide an industry standard vision interface, the data is sent to a protocol processor board based on a Xilinx Virtex 6 FPGA. This board takes the measurements from up to 16 sensors with 8 channels each, reorganizes the data to a consistent layout and implements a channel link based computer vision protocol to interface to a pc running the pattern recognition algorithms. In addition to providing the image interface, the protocol processor board also distributes trigger signals to the individual sensor subsystems.

The blackValue® sytem is capable of continually running complete frequency sweeps with 128 frequency lines on all four multiplexed channels in less than 1.3 ms which yields a measurement or frame rate of 770 Hz. Limiting factors include settling times after switching frequencies and after actuating the channel switches. As measurement on all channel groups happen simultaneously, adding more channels does not degrade frame rate. The total delay from the trigger event to the completed transmission of the measured data points was measured to be below 2 ms.

The sensor system is designed to be used in transmission geometry with the transmitter frontend mounted above and the receiver frontend mounted below the flow of plastic flakes in the air gap between the conveyor belt and an air nozzle bar. It is possible to position the receiver inside the conveyor belt to increase the timing budget for pattern recognition algorithms and air nozzle actuation, though this would introduce an additional layer of belt material into the measurement. Since this layer might get thinner through abrasive particles, might get covered in residues of unknown composition or might be inherently inhomogeneous, e.g., at its seam, the error introduced because of this layer is not constant over time and thus hard to calibrate out. For belts that are reinforced with metal strips or a metallic mesh, a measurement through the belt might not be possible at all. As the total measurement time is shorter than 2 ms and total time of flight of the particles is 33 ms, positioning the sensor at the end of the conveyor is favourable in this case.

Successful identification and separation of individual flakes of plastic depends on the flakes not overlapping during the measurement. To achieve a high throughput with a single layer of flakes, a wide conveyor belt is needed, which in turn necessitates a large number of sensor channels to cover the whole width with cm-range resolution. To keep cost low, it is preferred that these channels have only a limited bandwidth. Since the measurement bandwidth determines the range resolution of the sensor system and accurate thickness information helps with the robustness of the parameter reconstruction algorithm, a combination with a light section sensor or a time-of-flight camera (ToF camera) offers a cheap end efficient way to increase depth resolution of the sensor system.

The area around the air gap following the conveyor provides only limited space for the air nozzle bar and the multitude of sensors needed, hence it is favourably to position the sensor casing further back and guide the wave to where the measurement takes place. The case is designed such that each channel is brought out as a WR-10 waveguide flange. This simplifies production testing of output power and input sensitivity but puts a lower bound

on physical channel spacing. Focusing lens systems, open waveguides as well as dielectric tip antennas were evaluated as possible solutions to reach the required centimetre channel spacing [3]. Of those three, a short waveguide leading into a dielectric tip antenna has proven to be the most viable solution based on cost, achievable resolution and complexity of mechanical integration. Since these tips act as conformable dielectric waveguides, they provide a way to guide electromagnetic waves on complex trajectories and create line scan apertures without the machining required to realize such a system using metallic waveguides. To order to focus the transmitted wave onto the receiver, the dielectric tips are tapered, resulting in the antenna diagram shown in Fig. 3.



Fig. 3: simulated antenna diagram for the dielectric tip.

The use of these dielectric tip antennas imposes some restrictions on the achievable measurement geometry and configuration. Evanescent wave coupling between neighbouring waveguides becomes significant below a distance of two times the wavelength, 3.57 mm at 84 GHz, resulting in a minimum center to center channel spacing of 9.68 mm. Furthermore, the finite directivity of the tapered tips leads to a maximum distance between transmitter and receiver as a function of channel spacing. A 10 mm pitch and a 15 dB directivity angle of 80° result in a maximum clearance of 1.2 cm. To alleviate this tight restriction, our system is operating in TDM mode with only one in four channels active at any given time. This increases the maximum possible horizontal gap to 4.8 cm, enough space for typical shredded plastic flakes to pass through.

3. Object Classification

Because using full-spectrum time-domain spectroscopy is not feasible for our use-case of inline sensors in sorting applications, we use a small-band frequency-domain THz line-scan camera. The camera is used for machine learning techniques as deep-learning and statistical learning. We have to deal with real-time requirements during classification and thus cannot use very-deep learning using convolution models and pre-trained models like ImageNet [4]. Our algorithm is divided in three major steps: Preprocessing, pixel-wise classification and object classification. As a first step a preprocessing for noise reduction and normalization

of the antenna geometry is done. This step is comparable to the white-balance in optical systems. As we get complex-valued measurements of the absorption spectrum, we do a complex division by the recorded reference signal for normalizing. As we can update the reference value periodically, we can do normalization of basic belt pollution in this step, too. Therefore, reference measurements are periodically taken in transmission when no sample is present, summarizing the effects of the frequency-dependent intensity of the emitted wave and the attenuation by the conveyor belt.

The result of the complex division of the received wave by the reference wave is independent of the intensity of the emitted wave. This complex division is computed on the frame grabber in hardware for reducing the overall computational time used on CPU, because this step has to be done for every single THz pixel.

The second step is the pixel-wise classification of measurement data. This task has been focused in [5]. Although there are many classification methods in literature, most of them have the disadvantage that the model size and classification runtime cannot be controlled easily. For this reason we decide on methods whose model size can be controlled easily and is independent on the amount of data used for training. The third step is the aggregation of classification results for any pixels of an object as a decision input to the sorter. One can show that a simple addition of the classes' probability is feasible for our first test set. The algorithm decides for the class with the major probability or rejects in hard cases. This step has to be refined during integration in the full sorter in future.

4. Sorting system for industrial plastic recycling

In order to make the developed sensor technology applicable for plastic recycling, the THz sensor and the classification methods have to be integrated into an industrial sorting system. The practical evaluation of this novel technology is done in a stepwise manner within different experimental setups. First, the sensor technology is integrated and evaluated in a miniaturized experimental platform called *TableSort*. The *TableSort* platform is depicted in Fig. 4 and constitutes a fully functional sorting system including all relevant sensor and mechatronic components, e.g., different line scanning cameras, a controllable array of air nozzles and a conveyer belt.



Fig. 4: *TableSort*, a platform for rapid prototyping of sorting systems in the laboratory. (a) The *TableSort* platform exhibits all relevant components of a large-scale industrial sorting machine including devices for material transport, different sensors modules and a computer system for real-time controlling the sorting process. (b) Technical drawing of the *TableSort* system with integrated THz sensor and (optical) line scanning camera for plastic sorting.

The experimental sorting system has a dimension of approximately 1000 mm height, 1250 mm width, 450 mm depth with a sorting width of 180 mm and therefore allows for an easy

operation and by a single person. Furthermore, the experimental system is designed to receive various sensors and mechatronic components, and be able to mount them in arbitrary position and orientation. This is achieved by an optical breadboard-like construction which builds the vertically orientated base plate of the system.



Fig. 5. Fusion of high resolution line-scanning camera images and low resolution THz camera images.

Due it's flexibility, the TableSort platform is used to test different sensor and material transport configurations in a prototypical manner and to assess the achievable segregation of flakes of different types of polymers. Fig 4.b shows the integration of the THz sensor into the TableSort platform, able to measure and analyse the transmission of plastic flakes for material sorting. The position of the THz sensor was chosen in a way that the plastic flakes are transmitted during flight when the material leaves the conveyer belt. In doing so, only the absorption of the surrounding air, which is assumed to be a constant interference, has to be taken into account for the analysis of the measured THz signals. In addition, a conventional line scanning camera sensitive in the visible light spectrum (VIS) is integrated in the experimental sorting system. The purpose of the line scanning camera is its significant high spatial resolution compared to the THz sensor, which is physically limited due to the THz wavelength in the millimetre range. Both sensors are mounted in such a way that the scan lines of the line scanning camera and the THz sensor coincides, see Fig. 4.b. The data of the line scanning camera, i.e., the VIS images, are not used to classify the material but to enhance the spatial resolution of the THz sensor and the robustness of the classification result. Two problems arise from the low spatial resolution of the THz sensor. One problem is that the shape of the sample determined by the THz sensor alone is too coarse to allow a precise ejection by the air valves. This problem is getting worse when the material flow is too compact. The second problem arises when the material is only partly visible at one pixel of the THz camera or when different material flakes contribute to the detected THz signal. Ignoring this fact would add too much noise to the learning and the classification process. The data fusion of the THz and VIS image provides the possibility to recover the shape of the objects with a high spatial resolution, see Fig. 5. This can be either used to improve the ejection of the material or to detect pixels with a spectrum composed by two different materials resulting from neighboured or overlapping flakes. Furthermore, the VIS image can be used to improve the performance by identifying the location of the flakes in the image and disregarding all pixels of the background in the following processing steps.

In a following evaluation step, the developed THz sensor technology is integrated in a large-scale sorting system with 800 mm sorting width. For this, another rapid prototyping platform is utilized. The so called *FlexSort* platform, shown in Fig. 6, comprises a modular sorting system which is housed in a ship container. This allows to transport the sorting system to recycling facilities and to evaluate the sorting system and sensor technology in field tests under real-world conditions.



Fig. 6: *FlexSort* for rapid prototyping of large-scale sorting systems for industrial applications. The platform is housed in a transportable ship container, allowing to conduct field tests, e.g., in recycling facilities. The actual sorting system is modular and enables the testing of different sensor technologies and configurations.

5. OUTLOOK AND SUMMARY

To realize the high requirement for a 100% recycling cycle, new sensor concepts are under investigation. Especially for the recycling of black plastics, classic system approaches with hyperspectral cameras in the IR region show weakness. The combination of optical sensors with a THz line array in the lower THz frequency range seems to be a promising approach to sort black plastics. For industrial applications a low cost, high efficient camera concept is necessary. The first measurements show a high accuracy. Under consideration that a non-optimized software algorithm was used the results show a high potential for future developments and are a good basis for the development of a high frequency line array for sorting applications.

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