CHAPTER

9

Sensor-based sorting

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Sensor-based sorting (SBS) has been widely applied in the recycling industry for various waste types for more than two decades. Compared to manual sorting, SBS achieves higher throughputs, reproducible sorting results, and higher automation degrees. While the sortable particle features of traditional sorting methods (e.g., wind sifting or magnetic separation) are limited by the underlying separation forces (e.g., magnetic force), SBS methods are characterized by the independence of detected particle features (e.g., color and chemical structure) and the applied separation forces (e.g., air valves). Thus, a variety of different particle features can be used and combined for corresponding sorting tasks, and the sorting process can be easily adjusted by the applied sorting program. Therefore, sorting tasks such as sorting according to different colors or polymer types that were difficult or impossible to achieve with traditional sorting equipment can be achieved by SBS. Currently, sensor-based sorters are applied to various material flows, and SBS (cascades) represent a central element of many modern sorting processes.

9.1 MECHANICAL TREATMENT OF WASTE

Mechanical recycling chains generally consist of two treatment levels: *pretreatment*, the enrichment of valuable product fractions through preconditioning and sorting, and *recycling*, the production of secondary raw materials (Pretz et al., 2020). Taking lightweight packaging (LWP) waste as an example, it is first mechanically treated to enrich plastics according to their polymer type in sorting plants. Subsequently, sorted fractions are further refined and processed in recycling plants to produce high-quality recyclates. These are fed back into the anthropogenic material cycle to substitute primary raw materials in new good production.

In both treatment levels, sensor-based sorters equipped with application-specific sensors and in different construction types (e.g., belt and chute sorters) are applied. Due to distinct material compositions and characteristics, sensor-based sorters are located at different positions in the process chain. In most cases, SBS unit is positioned after necessary preconditioning processes (shredding, sieving, and sifting) as SBS

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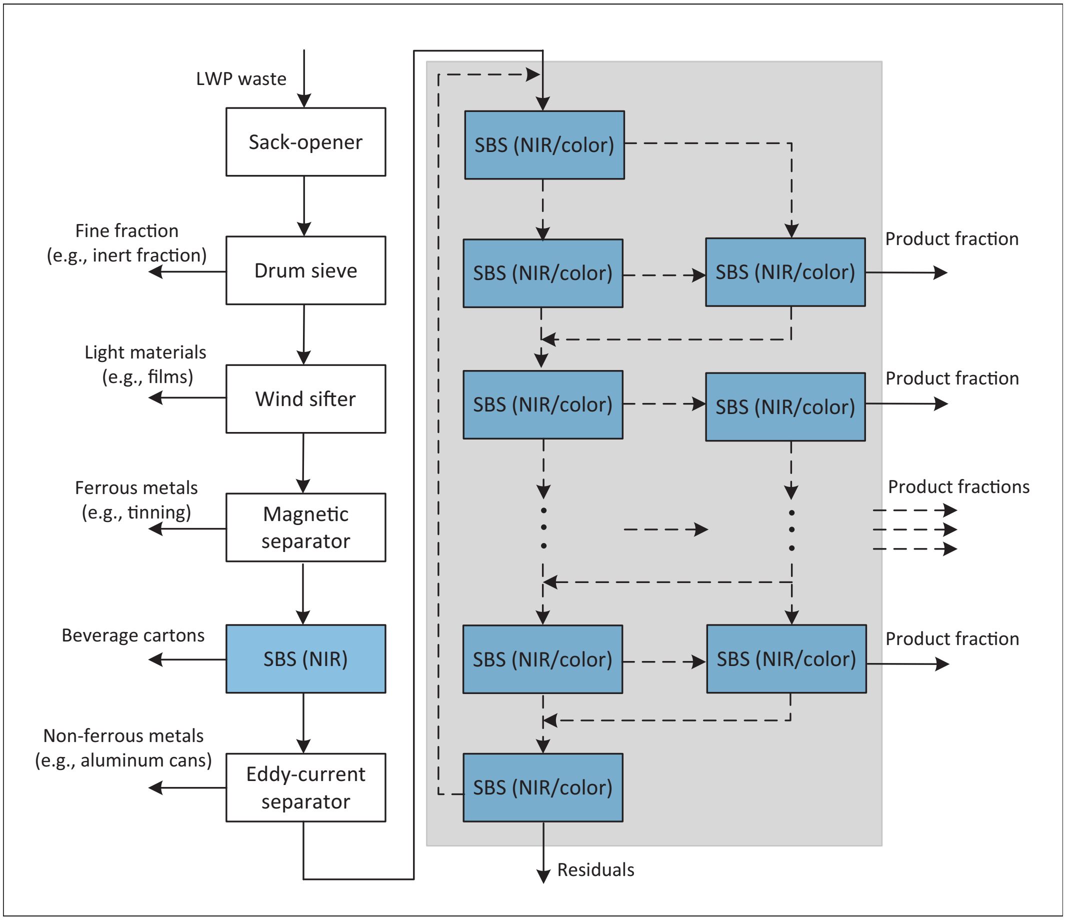


FIGURE 9.1 Exemplary and simplified mechanical treatment of lightweight packaging material in Germany. *Gray area*, SBS cascade.

processes require preconditioned materials. Figure 9.1 shows a typical sequence of mechanical treatment processes for LWP in sorting plants in Germany.

In LWP sorting plants, SBS is an important step through which valuable product fractions are sorted according to polymer types and colors. As shown in Figure 9.1, multiple sensor-based sorters with different sensors are placed at the end of the mechanical treatment process and generate the desired preconcentrates. Modern LWP sorting plants contain sorting cascades with typically more than 20 sensor-based sorters to meet the high requirements on material recovery and purity of the generated preconcentrates.

9.2 PRINCIPLE OF SENSOR-BASED SORTING

Despite the variety of covered sorting applications and construction types, all sensor-based sorters follow a similar principle of consecutive steps, as shown in Figure 9.2:

(1) feeding,
(2) detection, and
(3) separation.

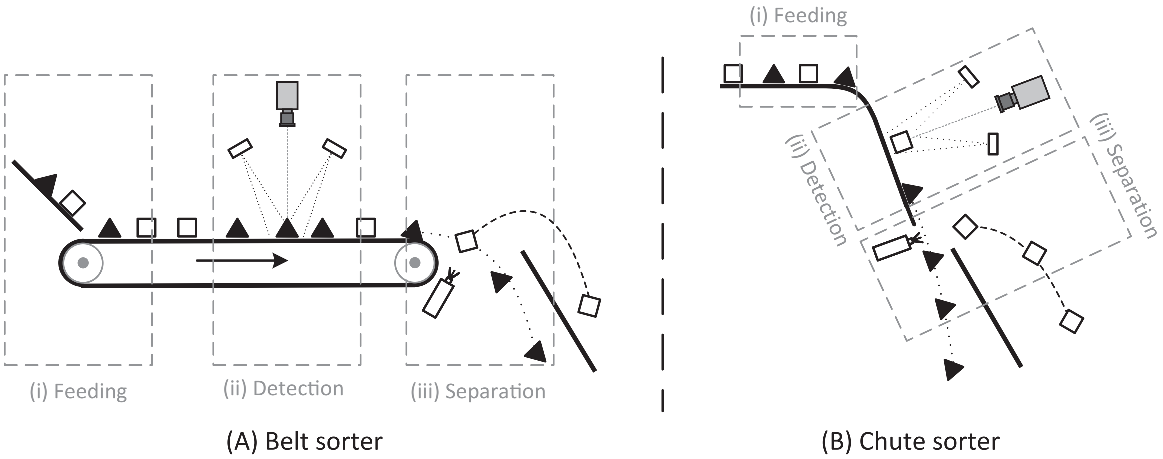


FIGURE 9.2 Construction types of sensor-based sorters. The three steps in sorting are indicated. The *black triangles* are the drop fraction; the *white squares* are the eject fraction.

In the feeding step, the material flow is uniformly distributed over the conveyor surface. The goal is to present the material flow as a *singled monolayer*, i.e., avoid overlapping or touching of particles and guarantee sufficient spacing between different particles.

In the detection step, the material flow passes through a detection area where one or more sensor units measure the (surface) properties of each object. Depending on the measured characteristics, the objects are typically irradiated with light from emitters in a particular wavelength area, and the sensor captures the reflected or transmitted radiation. The captured sensor data is then transferred to a calculation unit. In the calculation unit, (machine learning) algorithms classify the objects into different material classes or target fractions. Based on the classification result and a user-defined sorting recipe, a sorting decision is made for each particle.

Based on the sorting decision, a separation unit sorts the input material flow into two or more target material flows in the last step: separation. According to the sorting strategies, the target fraction, in the case of *positive sorting*, or nontarget fraction, in the case of *negative sorting*, are blown to one fraction called *eject*. The other materials are collected in the other fraction called *drop*.

Different mechanical separation forces can be applied to sort each particle in the desired target material flow. The most common separation systems by far are compressed air nozzle bars. With compressed air nozzles, particles with the sorting decision "drop" follow a parabolic trajectory at the end of the conveyor belt and end into the drop fraction. In contrast, particles with the sorting decision "eject" are shot with a few milliseconds of compressed air blast from coordinate-specific air nozzles into the eject fraction. In specific cases, the material flow can be separated into more than two fractions with more separation plates to different chambers through suitable compressed air nozzle settings or applying multiple nozzle bars. Other separation systems use mechanical paddles to change the trajectory of falling particles or mechanical grippers or vacuum cups to sort individual particles from the conveyor belt.

9.2.1 Construction Types

Two types of sensor-based sorters have become established in the state of the art: *belt sorters* and *chute sorters*. Belt sorters (Figure 9.2A) are typically applied in sorting plants for pretreatment of objects in relatively large sizes (≥10 mm, e.g., plastic bottles), while chute sorters (Figure 9.2B) are mainly applied in recycling plants for smaller particles (<10 mm, e.g., plastic flakes).

In SBS processes with belt sorters, the usually heterogeneous input materials are unloaded by a vibration chute or delivered from other conveyor belts with a lower speed to the acceleration belt with much higher belt speed (about 3 m/s) to ensure that the material flow is presented as a singled monolayer to the SBS unit. The throughput of a belt sorter depends mainly on the width (0.7–2.8 m depending on the application) and speed (up to about 4.5 m/s) of the belt conveyor.

Chute sorters differ from belt sorters in the transport of material flow: instead of being transported with a conveyer belt, objects go through the detection and separation area by sliding down an inclined surface; see Figure 9.2B. Compared to belt sorters, objects sorted with chute sorters have less relative movement, which is advantageous, e.g., for rolling objects. In addition, a transmission measurement with color cameras is possible, as the background of chute sorters is transparent, which leads to the wide application of chute sorters in glass sorting. Moreover, the object extraction and detection are—owing to the transparency of background—easier in the case of similar characteristics of objects and background, e.g., in sorting black plastics on black conveyor belts. However, due to the limited sliding speed, a chute sorter typically achieves relatively lower throughputs than a belt sorter.

9.2.2 Working Modules of SBS

Depending on the target of a single sorting step (high yield or high purity grade), a sensor-based sorter can work in different modules: rougher, cleaner, or scavenger; see Figure 9.3. The module *rougher* aims to sort a material flow with maximum yield, which results in a product fraction with a high amount of impurities. The valuable materials are then fed to a *cleaner* stage, the target of which is to sort the material with high purity, and the valuable material fraction is the end-product fraction. The residues of both rougher and cleaner can be re-sorted with a *scavenger* stage to recover valuable materials fed back to the rougher. Only a multistage sorting process can achieve both high purity of the output streams and high yield of valuable materials (Feil et al., 2021).

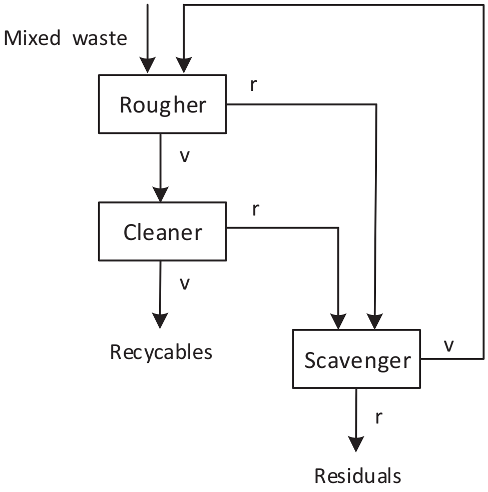


FIGURE 9.3 Different working modules of sensor-based sorters: rougher, cleaner, and scavenger. *v*, valuable materials; *r*, residuals.

9.3 REQUIREMENTS FOR OPTIMAL SORTING RESULTS

In SBS, adequate material flow presentation and preconditioning of the material flow is of utmost importance. Optimal conditions require adherence to the following requirements:

(1) Material flow presentation as a singled monolayer:

Overlapping or touching particles hamper the correct detection and sorting of particles. As most sensors measure the particle surfaces or have a limited penetration depth, only the material layers on top are detected, based on which the sorting decision is made. Depending on the combination of overlaying and underlaying materials, overlapping leads to false discharges and lower product purity (non-target material is overlapped by target material) or lower yield (target material is overlapped by non-target material). Furthermore, touching or overlapping particles may be recognized and sorted as one object, resulting in lower purity or yield depending on the applied classification algorithms. For air-nozzle-based sorting, touching particles or limited particle distances may also result in particle entrainment of lighter particles close to target materials and thus lower product purities. In addition, for transmissive sensor measurements, e.g., XRT or RGB, or sensors with limited penetration depth, e.g., NIR, overlapping particles can lead to misclassification (e.g., mixed NIR spectra of overlapping particles) and false discharges.

(2) Limitation of grain size ratio:

As the compressed air settings and optimal air nozzle distances depend on the particle sizes, a limited grain size ratio of the material flow is necessary. Furthermore, the reflected radiation differs between different particle heights. Optimally, the maximum to minimum grain size ratio for sensor-based sorters should be lower than 3 to 4.

(3) Removal of flyable 2D fractions:

To guarantee a particle discharge at the right time and position, the relative movement of objects on the conveyor surface must be minimized. Consequently, flyable 2D fractions such as plastic films should be separated before SBS, or adapted airflow guidance should be used to minimize their relative movements on the conveyor surface.

(4) Removal of fines:

The available sensor resolution and air nozzle distance determine the minimum particle size to be sorted. Fine particles are more likely to be swirled up on acceleration belts. They can deposit on conveying surfaces or components of the sorting unit due to air turbulence during particle discharge with air nozzles. To avoid such process disturbances and a decrease in the sorting performance, fine fractions should be removed during preconditioning before the SBS process.

(5) Minimization of composite materials:

Composite particles and particle surfaces with contaminations (e.g., adherent organics) negatively affect the SBS process. In some applications, composite particles may be liberated by adequate comminution processes. Further preconditioning may be applied to remove contaminations from particle surfaces before SBS, such as hot washing of plastic flakes. For waste collected in bags, effective bag opening is of vital importance for sufficient sorting results.

9.4 AVAILABLE SENSORS

The choice of appropriate sensors for the intended applications is crucial to capture distinct particle and material characteristics for optimal sorting results. In the last two decades, various sensor technologies have been further developed and applied to SBS. Some sensors are able to detect similar characteristics but are applied in different material flows or positions in a process chain due to their specific measuring principle and the economic aspects (conflict between cost-benefit and cost-expenditure).

9.4.1 Color Detection

Sensors for color and particle shape detection are widely used in SBS. Image sensors measure the intensity of visible light (VIS), covering the wavelength range of 380–780 nm. An image sensor consists of a large number of light-sensitive semiconductor elements, which convert the incident electromagnetic radiation into charge units. The charge units are accumulated over the exposure time and converted into a digital number that describes the intensity of the radiation. The radiation incident on a semiconductor element is transferred into brightness information (pixels). For each spectral region, the radiation intensity of that spectral region is measured.

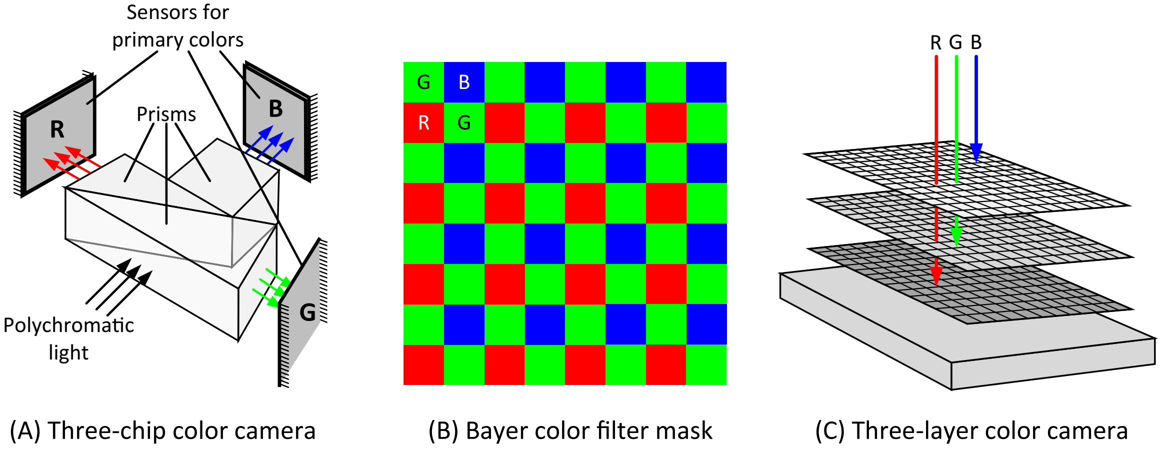
Traditional and widely applied VIS sensors are red, green, and blue (RGB) sensors, which measure the intensity in three spectral regions. In the last decades, hyperspectral imaging in the VIS area was introduced and is increasingly applied for more accurate color detection and classification.

9.4.1.1 RGB Sensors

With RGB sensors, the radiation intensity of the three basic colors RGB is measured, through which their color components can be determined. The original color is identified with the three color components by additive color mixing. In this way, the color is represented approximately, and the number of possible colors depends on the depth of each spectral channel. Widely used RGB cameras have 8-bit or 12-bit spectral channels. For an 8-bit channel, each color component (R, G, and B) can have 256 (= 2^8) different brightness levels; thus 256^3 different colors can be identified by mixing the three primary color brightnesses. The detection of the RGB components can be technically implemented in various ways, presented in Figure 9.4.

Three-chip color cameras (Figure 9.4A) have a separate sensor for each primary color. The incident light is split into the three primary colors RGB via upstream prisms and directed to the respective sensor. Each sensor thus receives the brightness of a color channel.

In color detection via a color filter mask (Figure 9.4B), a color filter that only allows specific spectral ranges to pass through is applied directly to a sensor. A pixel thereby only receives the brightness of a specific color channel. There are various color filters, with Bayer filters (Figure 9.4B) being the most commonly used ones due to their low cost.



(A) Three-chip color camera (B) Bayer color filter mask (C) Three-layer color camera

FIGURE 9.4 Technical implementation of RGB cameras, showing the camera setup (A), the color filter mask (B), and a three-layer color sensor (C).

In a three-layer color sensor (Figure 9.4C), three pixel layers are arranged one above the other. In each pixel layer, the light of a different wavelength range is absorbed and converted into charges, which enable the determination of the RGB color components.

RGB cameras can be applied in almost all applications where color and shape play an important role. For example, in glass and plastic recycling, RGB cameras are applied to sort flakes into different color fractions. Furthermore, they can be applied in separating glass, ceramics, stones, porcelain, and metals.

9.4.1.2 *Hyperspectral Imaging*

While RGB sensors only measure the intensities of the three RGB spectral ranges, it is possible to capture the intensities of more than 100 spectral ranges using hyperspectral color imaging. This image information can be displayed in a hyperspectral cube (Figure 9.5A). In the hyperspectral cube, the spatial image information of a sensor (x,y) is represented in two dimensions and the spectral image information λ in a third dimension. The number of elements in the (x,y)-plane corresponds to the spatial resolution in pixels. Depending on the spectral resolution, there are k elements in the λ-direction: $k = 3$ corresponds to RGB cameras, and for hyperspectral imaging, k has the value of ≥ 100.

There are several ways to acquire hyperspectral image data. A similar basic principle applies to all acquisition modes: a maximum of two dimensions can be read from the hyperspectral data cube using a two-dimensional area sensor. The third dimension is acquired by multiple sequential measurements. Since point area scanning does not allow the sample to move, a line scanning model (Figure 9.5B) is used in SBS.

In line scanning, the incident light of the object to be measured enters the camera through an entrance aperture (slit). A two-dimensional dispersing element (diffraction grating or prism) generates a spectrum for each point of the line and distributes it over the second dimension of the detector. Therefore, the wavelength range can be arranged according to the position of the detector. By moving the object to be captured or the sensor unit forward, the t-direction in Figure 9.5B, objects can be detected line by line. Hence, this approach is particularly suitable for conveyor belt systems and real-time applications.

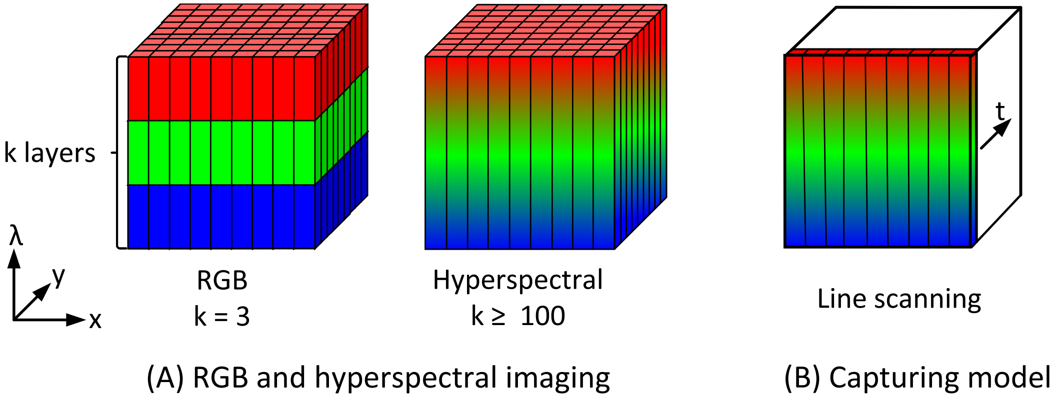


FIGURE 9.5 RGB and hyperspectral imaging showing in the hyperspectral cube and the capturing model in sensor-based sorting.

9.4.2 Near-infrared Sensor

Near-infrared (NIR) spectroscopy is based on the interaction between electromagnetic radiation in the NIR region and molecular structures of the material. NIR-sensitive chemical structures of specific materials absorb the energy of irradiation in specific wavelengths, which results in different levels of decreases in the reflected spectrum. The observation of absorption bands makes the analysis of material physical properties and chemical structures possible and thus enables their classification. The irradiation of NIR covers the wavelength interval between 780 and 2500 nm. As most NIR sensors have more than 100 spectral ranges, the capturing of NIR spectra also belongs to hyperspectral imaging.

NIR spectroscopy is dominated by overtones and combination bands, especially H-containing functionalities, e.g., CH, OH, NH, due to the low mass of hydrogen (H). Most polymer backbones, for example, contain NIR-sensitive functionalities such as CH, OH, NH, C=O and, frequently, the combination of them. These specific chemical structures lead to a characteristic spectrum of each material. Figure 9.6 shows the general raw spectra of five widely used polymer types: polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC).

In state-of-the-art sorting plants, the applied NIR sensors cover the irradiation range of about 900–1800 nm (*gray marked area* in Figure 9.6). Different manufacturers of SBS equipment may

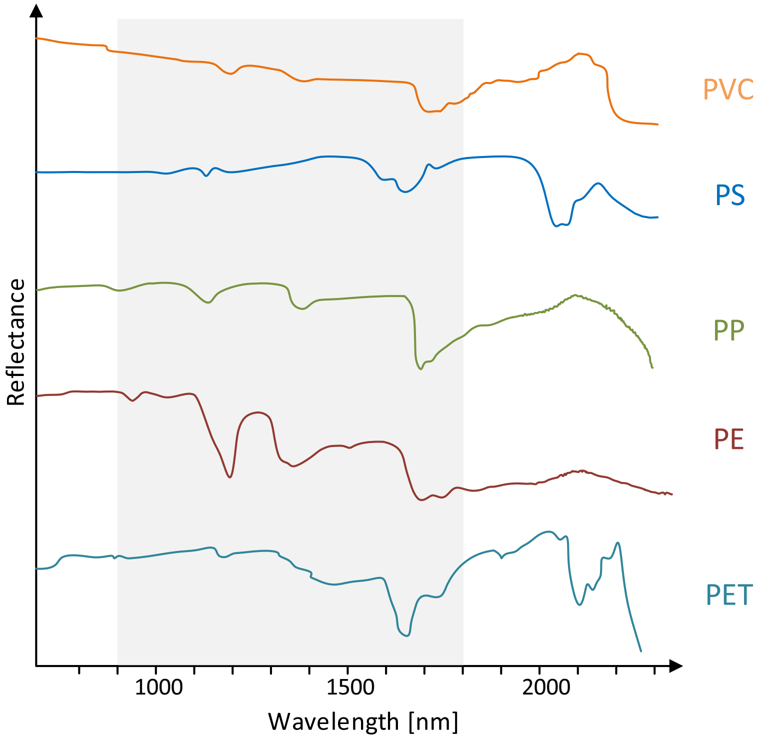


FIGURE 9.6 NIR spectra of widely applied polymers. *Gray marked area* is the typical range of sensors in sorting plants.

choose different wavelength ranges, depending on the specific target applications.

Due to the NIR-active chemical structures of polymers, wood, paper, and minerals, NIR sensors are widely used in, e.g., plastic, wood, paper waste, and construction and demolition (C&D) waste recycling. However, NIR spectroscopy has a limitation in detecting materials containing carbon black as a coloring agent, as they do not reflect sufficient radiation for spectral analysis.

9.4.3 3D-Laser Triangulation

3D sensors used in waste recycling are noncontact measurement methods for determining the three-dimensional shape of objects. For material flows, the 3D information is mainly used for particle detection and extraction and can be used for volume flow calculation. The most often used measurement is based on 3D-laser triangulation (3DLT).

In the 3DLT light-sectioning method, a laser line is irradiated onto the surface to be measured. An area camera then captures the laser beams reflected from the surface at a specific triangulation angle α (see Figure 9.7). This triangulation angle between the laser and the camera results in a lateral deflection of the laser beam as a function of the respective object height. With trigonometric relations, the object height and the one-dimensional profile of the measured object can be calculated from the lateral deflection of the laser line. Several one-dimensional profiles can be captured and assembled into a three-dimensional shape through relative movements between the object and the laser line. In SBS applications, objects are moved through the laser line and camera capturing area by a conveyor belt. Figure 9.7 shows the principle of laser triangulation using the light-sectioning method as an example.

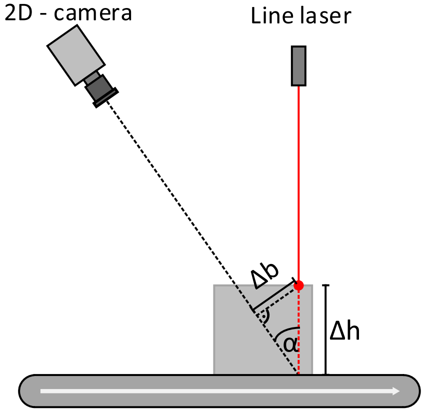


FIGURE 9.7 Working principle of 3D-laser triangulation (3DLT).

The size and location of the camera determine the limits of the measurable height range. Objects with surfaces containing large slopes or steps can shadow or cause multiple reflections of both the projected laser light and the light radiating to the camera. Shadowing caused by inclines, steps, or low depressions can be avoided by dual-camera 3DLT. In dual-camera 3DLT, a second camera is placed at the other side of the laser, with which both the front and back of objects can be captured.

Due to the high spectral power density of the laser radiation, the detection of the objects is not influenced by ambient light. Thus, surface detection is mostly independent of the object's color and material design. Exceptions are absorbing as well as reflecting surfaces. These cause too little diffuse reflection of the laser light, so that these surfaces cannot be adequately detected. In the case of transparent or partially transparent materials (e.g., transparent PET bottles in lightweight packaging waste), internal scattering of the laser light occurs, which widens the measurement spot and causes misdetection. The light can also be reflected twice, as it forms a light spot on the front and back sides, leading to detection error in object height. As hollow spaces can often not be illuminated by the applied laser, they cannot be detected and are thus included in calculating volume, leading to a higher measured volume than the actual volume.

9.4.4 Laser-Induced Breakdown Spectroscopy

Laser-induced breakdown spectroscopy (LIBS) is widely used in aluminum recycling for alloy detection. While other sensors used in recycling processes are line or area sensors, LIBS measures only one point at the same time. LIBS is an automatic emission spectroscopy through plasma ignition (at about 10,000–20,000°C) with a high-energy laser pulse as an excitation source. The constituent elements and molecules of the target material are decomposed, and the electrons are lifted to a higher energetic level from their ground state. During the plasma cooling process, the emitted electrons revert to their original energy state and emit characteristic optical radiation.

In practice, the laser energy concentration is increased by a focusing lens to form a plasma on the sample surface; see Figure 9.8. The plasma emission is collected with a collection lens and transferred with fiber optics to a spectrometer to disperse light and then measured with a detector. The detector usually consists of color sensors with a spectral range of 200–800 nm. The results of LIBS are shown as spectra containing peaks at certain wavelength areas. Depending on the spectral range and resolution of the detector, specific elements can be determined. A quantitative elemental composition determination can be achieved with an element-specific calibration, as the detected peak intensities reflect the quantitative composition.

As all elements emit light during plasma, LIBS can be used to determine the elemental composition of any object, regardless of its physical state (solid, liquid, or gas). Besides, as plasma is generated, no or only marginal sample preparation is necessary for most applications. In specific applications, coordinate-specific laser shots can clean the surface and remove impurities before applying LIBS. However, as LIBS forms plasma and is thus a destructive process, it damages the surface of samples. To avoid damage to the conveyer belt, LIBS is often combined with other sensors, e.g., 3DLT, to determine the object's position. As LIBS measures only characteristics of one specific point of an object, determining the elemental composition of inhomogeneous objects can be problematic.

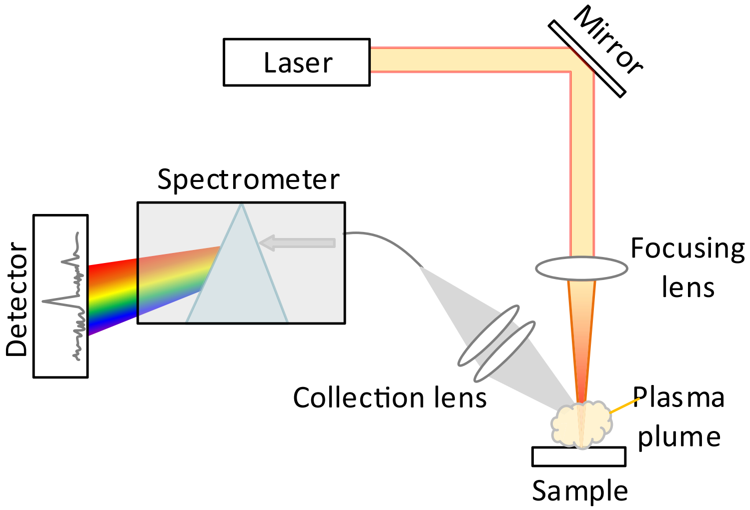


FIGURE 9.8 Setup for LIBS capturing and analysis.

9.4.5 X-Ray Sensors

X-ray covers the wavelength range of 0.001–10 nm. In waste-sorting applications, X-ray is mainly used in two different ways: fluorescence and transmission. With both technologies, the X-ray radiation is generated artificially, e.g., by an X-ray tube. As X-rays ionize matter and may damage the DNA of tissue, its illumination area must be protected.

9.4.5.1 X-Ray Fluorescence

X-ray fluorescence (XRF) analysis is based on observing secondary fluorescence caused by the excitation of atoms and ions using X-ray radiation. The sufficient energy of X-ray dislodges the electrons from the atom's inner shell, making the atom unstable. Electrons from the outer shell replace the released electrons, during which characteristic energy (fluorescence) is emitted (Figure 9.9). This energy corresponds to the binding energy of the inner and outer shell, which is characteristic for a specific element and thus enables a determination of the element type.

The fluorescence is captured through wavelength or energy dispersion. While *wavelength dispersive XRF* requires collimators and a crystal to parallelize and scatter radiation and uses a scintillation counter as a detector, *energy dispersive XRF* requires no specific optics and uses a semiconductor detector to differentiate between different wavelengths. This leads to a much higher spectral resolution of wavelength dispersive XRF and a much shorter measuring time of energy dispersive XRF.

XRF analysis is suitable for detecting heavy elements, for example, in sorting precious metals, metal scrap, and lead glass. Because of the high requirement on measuring time in sorting applications, only a limited number of elements can be detected instead of the complete composition of each particle.

9.4.5.2 X-Ray Transmission

X-ray transmission (XRT) sorting is based on the characteristic of X-ray that it can penetrate objects and thereby is attenuated. The attenuation of X-ray correlates with the material type (atomic densities) and the material thickness.

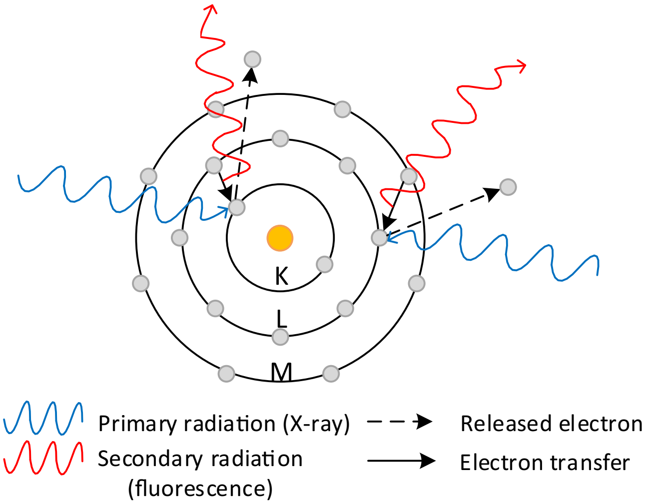


FIGURE 9.9 Working principle of X-ray fluorescence.

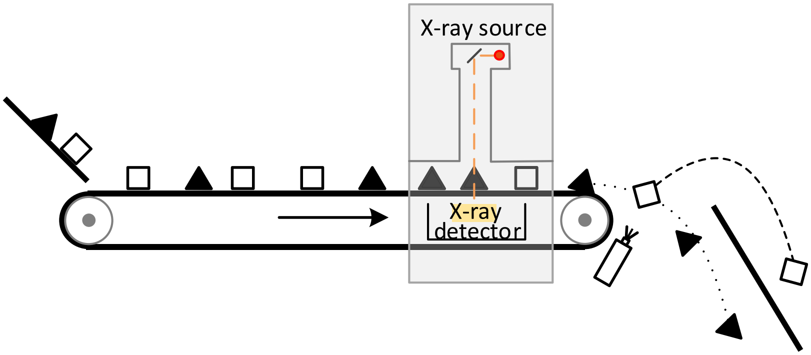


FIGURE 9.10 XRT-based sorter construction. *Gray area*, encapsulated area.

By capturing the remaining transmitted radiation with an X-ray detector, the characteristic intensities make the material determination possible. As the transmission is measured, the X-ray detector and X-ray generating source are placed on different sides of the measured objects and the conveyer belt (Figure 9.10).

As both thickness and the absorption coefficient influence the absorption/transmission intensities of X-ray, interpretation problems may arise in the case that objects with different thickness and different atomic densities are measured and analyzed. For example, a thicker object with low atomic density and a thinner object with high density may have similar intensities, which makes a determination of the material type impossible. To address this problem, dual-energy XRT with two single energy detectors is applied through two simultaneous measurements in different wavelengths: a filter is applied to ensure that only high-energy radiation can reach the second detector, through which the two detectors work at different energy levels. Combining intensity data from both detectors makes eliminating the influence of object thickness possible: compared to reference materials, objects can be classified as elements in high density and low density.

In sorting applications, materials with different atomic densities are principally sortable with XRT technology, and it is widely applied in battery and metal recycling, for example, sorting copper-containing particles from shredder scrap. However, the measurable particle thickness is limited by radiation source power, and compared to other light sources, X-ray technology requires great effort for shielding and radiation protection.

9.4.6 Induction Sensors

In sorting plants, metallic objects are often separated from other materials with conventional processes such as magnetic separators and eddy-current separators (Figure 9.1). However, some metallic components, e.g., stainless steel and composite materials, cannot be sorted with these processes. In this case, an induction sensor based on the measurement of material electrical conductivity is applied. One sensor generates an electromagnetic field at the active surface by an oscillator, and the approach of conducting materials to the active area causes a change in current in the oscillator. By detecting the current change, conducting materials can be detected.

Unlike other sensors, no radiation sources are necessary for induction sensors. To detect conducting materials over the entire width, a sensor bar consisting of several small sensors emitting electromagnetic waves is positioned under the conveyer belt or chute. The position of sensors corresponds to the position of measured objects, which leads to limited spatial resolution (>10 mm) due to the minimum sensor size. In addition, the signal intensity depends on the object's position on the belt or chute.

Induction sensors are mainly used to recover residual metals, as all kinds of conducting materials can be detected even if they are relatively small. For example, all kinds of metals can be detected for particle size greater than 1 mm. Induction sensors are applied in sorting different kinds of wastes, for example, shredder scrap and electronic scrap.

9.4.7 Other Sensors

Other sensors that can be used in sorting applications are, for example, mid-infrared (MIR) spectroscopy, radar/lidar, Raman spectroscopy, laser-induced fluorescence, and acoustic sensors. However, these technologies are under investigation and not widely used in existing sorting or recycling plants yet, or mainly used in the mineral industry. MIR spectroscopy, for example, can be applied in plastic classification and overcomes NIR's limitations in black material classification and additive detection in plastics (Becker et al., 2017; Signoret et al., 2020) but shows lower spectral resolution and currently has higher cost. Radar/lidar is increasingly used in research for volume determination to overcome the limitations of 3DLT, e.g., the limited measurement of transparent objects.

9.5 APPLICATION OF DIFFERENT SENSORS IN RECYCLING

Due to the different measuring principles, different sensors are used for different applications, and in the same plant, several sensors are applied for different purposes. For example, in LWP sorting plants, NIR sensors are used for sorting according to plastics type, and RGB sensors are applied in color sorting (e.g., sorting PET into blue, green, and transparent; see Figure 9.1). Table 9.1 shows different sensor characteristics and application examples of each sensor in the recycling industry.

TABLE 9.1 Characteristic and application examples of sensors in recycling.

Sensor	Radiation wavelength (nm)	Active materials	Measured characteristic	Application in recycling
RGB/ VIS-HSI	380–780	All visible materials	Color, 2D shape	Plastic, glass, paper, ceramics, mineral
NIR	780–2500	E.g., plastic, beverage cartons, wood, paper, minerals	Material type	LWP, paper, C&D waste
3DLT	- (Laser)	All nontransparent materials	Particle 3D shape, volume	Volume calculation; position determination (e.g., with LIBS)
LIBS	- (Laser)	Principally all elements	Material type	Aluminum, metal alloys
XRF	0.001–10	Heavy elements	Material type	Metal, lead glass, aluminum, zinc
XRT	0.001–10	Materials with a difference in atomic density	Atomic density	Battery, aluminum, wood, compost
Induction	- (electromagnetic field)	Metals	Electrical conductivity	Shredder scrap, electronic scrap

Recent research has broadened possible applications for different sensors by extracting specific characteristics. For example, in plastic recycling, XRT can detect flame retardant in plastics (Vrancken et al., 2017), and LIBS, in addition to MIR, can detect and classify black plastics (Huber et al., 2014). Also, NIR can be applied in determining calorific value, moisture, and chlorine content in refuse-derived fuel (Vrancken et al., 2017).

9.6 RECENT DEVELOPMENTS

In the last several years, many investigations in SBS and recycling have been conducted, through which the detection and classification accuracy, the sorting efficiency, and yield were increased (Gundupalli et al., 2017). The sensor resolution, frame-rate, and sensitivity were improved, which led to a more precise detection in both spatial and spectral direction.

The separation unit was upgraded with robotic arms in specific applications, which pick up valuable materials through grabbing or pneumatic force (Sarc et al., 2019). Compared to air nozzles, robotic arms enable the separation of multiple target fractions in one sorting step and result in fewer false-negative discharges. However, they are characterized with a lower throughput as the robotics arms can only sort one object after another. Thus, they currently achieve much lower throughputs and yields compared to air-nozzle-based SBS.

To detect and extract the material characteristics more precisely, multisensors are applied in specific applications. For example, in sorting C&D waste with robotic arms, color sensors, 3DLT, and NIR sensors are applied. Through sensor fusion, a product fraction in right color and right material type with high purity can be generated.

In data analysis, machine learning models were improved both in prediction accuracy and computational time. More and more machine learning models were tested and applied to reach optimal sorting results. Recently, deep learning techniques, e.g., convolutional neural networks, were applied to sort materials into more detailed classes (Gruber et al., 2019; Yu et al., 2020). As a result, PE silicon cartridges, for example, can now be separated from PE product fractions based on form and texture.

9.7 OUTLOOK

With these improvements, more and more characteristics of material flows can be extracted. Besides applying sensor technology in recycling processes for sorting, applications of sensor-based material flow characterization (SBMC) are an upcoming research topic (Kroell et al., 2021).

In SBMC, the goal is to characterize material flows based on acquired sensor data. Based on the extracted material flow characteristics, new applications and optimization potentials in sorting and recycling plants are envisioned. Possible new applications include real-time characterization of input material flows, sensor-based monitoring and early detection of process disturbances, predictive maintenance, real-time product quality monitoring, implementing adaptive process control algorithms, and obtaining a better process understanding (Kroell et al., 2022).

For example, through volume determination and a comparison to the capacity of different aggregates, the feeding of the plant or specific machines can be adjusted. Without adding new sensors to the sorting plant, the data of existing sensors could be used for SBMC, and machine parameters could be adapted online.

Sensor technologies have provided possibilities in sorting and recycling different waste material flows through rapid detection and classification and accurate separation of product fractions. Today, sensor technologies face challenges such as more complex material compositions, higher requirements on production fraction purities, and higher recycling rates to enable enhanced material recirculation in the context of a circular economy. Improvements in sensors, peripherals, and data analysis are further investigated to meet increasing requirements and demands. Sensor technologies still offer considerable potential in contributing to performance increases of sorting plants, recycling plants, and the value chain through SBMC in upcoming years.

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