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ADVANCED SORTING TECHNOLOGIES AND ITS POTENTIAL IN MINERAL PROCESSING

1. Introduction

In many mineral processing installations it is of critical importance to provide an efficient mineral purification. It is carried out by complicated processing steps involving grinding to very fine particle sizes and further separation. However, purification of the coarse feed particles before grinding can provide significant benefit in overall energy efficiency and the final product purity. When the particles representing impurities can be separated before grinding they do not contaminate a feed stream for further processing and additionally they are not unnecessarily ground. This can be achieved by optical sorting carried out before the grinding stage when the particles have sizes in a range of several centimetres [1].

A newly developed optical system at Comex makes it possible to identify and separate different mineral particles regarding their colour, shape, pattern, size and indirectly their composition. This results in high purity product output reaching even 99–99.9%. High precision rejection system brings a new possibility to remove waste particles without excessive removal of product material to the waste fraction. It is especially important when particles are positioned with high density during analysis and rejection to provide high capacity separation.

2. Separation system configuration

The standard separation system from Comex can be used in two configurations. Both configurations are illustrated on Figure 1. The image analysis system includes an optical

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camera installed at the discharge of the belt conveyor close to the rejection zone. The second configuration includes the camera or other sensors installed over the belt. In the first configuration the particles are analysed in free fall, while the second configuration concerns analysis carried out on the belt. Optical properties can also be analysed over the belt, however, it will be necessary to remove the belt background form each image, which is more difficult. Therefore, the configuration illustrated on Figure 1 is optimal for complex particle analysis and sorting.

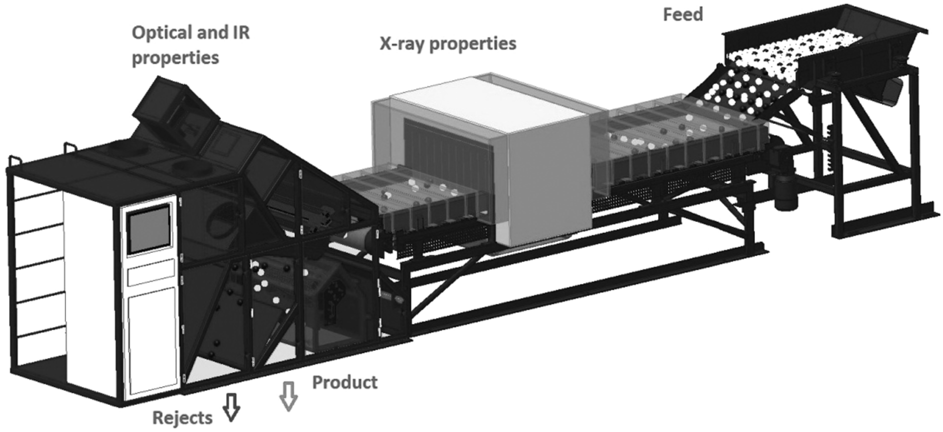

Fig. 1. Comex optical sorting system — configuration with the analysis at the belt discharge and X-ray analysis over the belt

The system is operated by an industrial PC based control system employing a separation algorithm based on selected separation criteria. Each particle is identified as regards the material or combination of materials, its dimension, shape, structure and its position on the conveyor. The particles recognised as the waste fraction are rejected by the air nozzle system or the mechanical flaps (for larger particles over 100 mm). The particles related to the concentrate fraction are normally falling in to the belt discharge area. This configuration is used when the amount of waste particles is significantly lower than in the concentrate fraction. This reduces the compressed air consumption for rejecting particles. In the contrary case, if necessary, the system can be easily converted to reject concentrate particles from the waste stream.

The sorting system configuration is very much dependent on the processed material and its characteristics. The configuration with analysis over the belt, is basically used when the image analysis requires very long processing time. When one image is under scanning the previous one (already scanned) is under analysis and electronic filtration. When ready, the information about the waste particles is stored in an electronic buffer for further rejection. This configuration is very typical when sophisticated mathematical models are used for recognizing the waste particles. It is also used when other analysing techniques are employed like thermal cameras or X-ray sensors, which require very long processing time when compared to the standard optical cameras. Another advantage of such configuration is related to the fact that the scanned particles are very stable on the belt surface during image scanning. This provides high quality images for further processing. The limitation of this system is related to the image scanning possibilities. In this case only a single side of a particle can be scanned as the other side of a particle is facing a belt surface.

The analysis at the belt discharge as shown on Figure 1 for optical properties can be used when the image processing and electronic filtration is relatively short in time. There is a strictly limited time period between the moment when the last image is ready analysed and filtered, and the moment when the first rejection can take place. The important advantage is related to a possible double side scanning of the falling particles by using two cameras above and below the analysed particles.

3. Analyzing device

Most of the optical separation systems available on the market today employ the optical properties of the processed material as a basic feature for separation [5]. However, many other characterization principles can be employed to recognize particles which have the same optical features. Comex optical separation systems can employ other mineral properties for further separation as: thermal properties, magnetic properties, chemical properties on the particle surface and X-ray attenuation properties.

3.1. Colour analysis

Standard optical separation is based on the optical image analysis where the separated particles are identified on the base of their colour and shape. Very often different colour particles containing different minerals are separated from a stream of particles which represent a product fraction. The same can be used for shape analysis where unwanted particles, which are misshaped or have different elongation factor, are removed. Figure 2 shows the typical sorter performance expressed by grade-recovery curves. In this case the calcite particles were processed to remove all types of grey and black coloured particles to achieve the whitest possible concentrate fraction. The feed material had a concentration of about 55–60% of the white particles. In the final product the concentration was increased to 88–98% but at the same time loosing from 8–16% “good” particles in the waste fraction. Therefore, this process has to be optimized against the required purity of the final product and allowed loses in the waste fraction. In case both are important, it is necessary to apply multiple stage sorting where the wasted particles have a chance to be processed again to be finally recovered as the product.

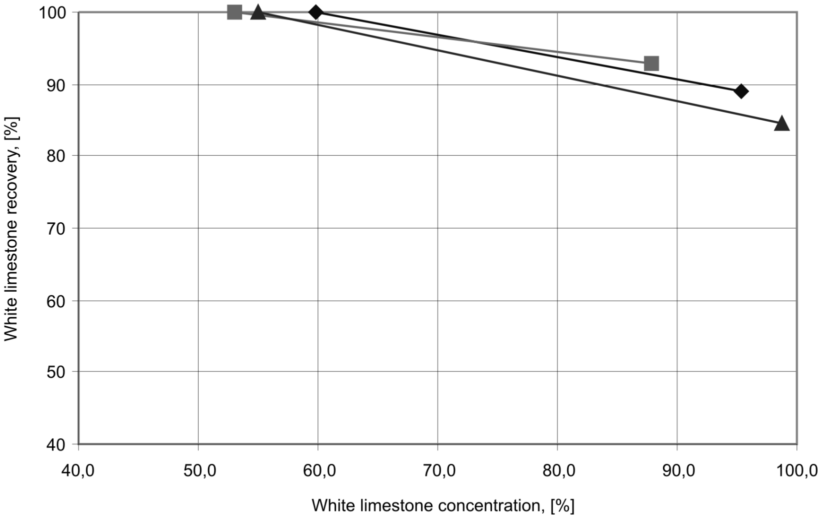

Fig. 2. Comex optical sorting example — upgrading of limestone particles having 55–60% concentration of white particle in the feed to 88–98% in the product

3.2. Shape and pattern recognition

The image separation software can provide quite sophisticated shape analysis. One of the advanced system features is related to the pattern recognition. This function allows introducing of the required shape or colour pattern into the reference particle description. Then, during investigation of any image the reference pattern can be verified and compared with all other particles. The recognition is carried out by the mathematical model, which verifies a score during matching with other particles. By specifying minimum score level the system recognises particles closest in shape or colour to the reference sample. When found, the particle is selected for rejection. Figure 3 shows an example of pattern matching.

The reference sample has been defined and saved in the software before the process stared. Then, the image was analysed with several other particles included. The found particles (three) are marked by squares. Searched particles are found even when being rotated, magnified or placed in the other part of the image frame.

3.3. Thermal properties

A combination of the standard optical separation device with different types of cameras can provide a new very sophisticated system. An application of thermal cameras can provide additional information about the material properties, which are not achievable by standard optical devices. The processed material is pre-conditioned before the separation to achieve a homogenous temperature in the range of 60–100ºC. When the particles are then distributed on the transport belt they are exposed to a cooling effect. An additional fan or blower is applied to provide a fasted cooling effect. Then, the particles are analysed by a thermal camera. In this way the material can be separated on the base of a relation between specific heat and heat conductivity as well as surface properties. Particles having larger surface and the same specific heat will reach lower temperature faster than the other ones. Materials with differences in heat conductivity and specific heat will provide even more possibilities to distinguish such particles. Thermal properties of a material can be very much affected by moisture content. Therefore, it is necessary to consider this parameter especially during separation of rocks and minerals coming directly from a mine.

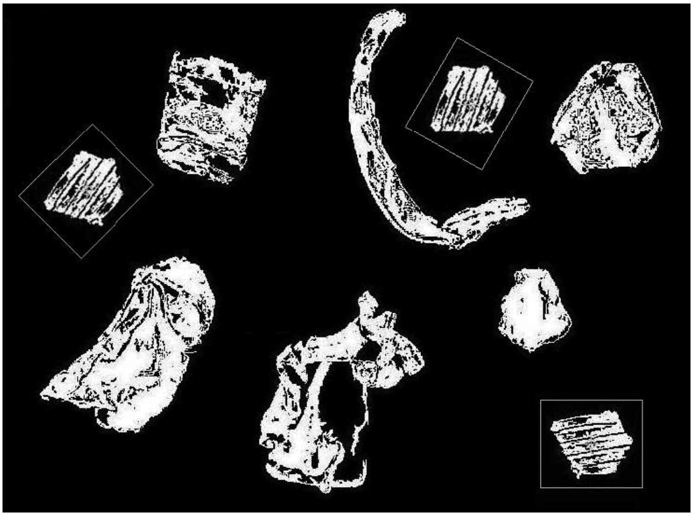

Fig. 3. Example of the pattern matching with the defined particle shape

3.4. Particle surface chemical properties

Separation of different materials can be also carried out by employing differences of chemical properties of processed particles. For practical application two types of surface changes can be considered. The first type is related to significant colour variations under chemical treatment. Then, the optical sorting system can be adjusted to identify different colours separately and thus recognise particle materials. This type of separation has been tried for e.g. Zn particles, which are very difficult to identify in the Al stream by visual test [2–4]. Second type of chemical treatment is related to possible changes of surface properties of the tested material. It is possible to modify a material surface by molecules of different chemicals so the material changes its properties against water and some water based solutions (similar mechanism to flotation principle). This type of modification can provide the material surface being hydrophilic or hydrophobic. Then, by spraying such materials with water based solutions of a fluorescent substance, and using UV light, it is possible to recognize different patterns of water agglomeration on the material surface. This type of separation has been carried out with various chemicals to modify surfaces of separated metals (Al, Zn and Cu) [2–4].

3.5. X-ray transmission based systems

Almost all optical separation methods are based on the image analysis regarding particle shape, geometry and colour. However, the internal structure of particles is not analysed, as it is invisible for cameras. The application of X-rays can provide much better information regarding the internal material structure and other material contamination.

The intensity of individual pixels on an image created after X-ray transmission is depending on mass attenuation coefficient. This factor is very individual for different materials. A narrow beam of monoenergetic photons with an incident intensity I_0, penetrating a layer of material with mass thickness x and density ρ, emerges with intensity I given by the exponential attenuation law

$$I/I_0 = \exp\left[-(\mu/\rho)x\right] \tag{1}$$

It means that the image after X-ray transmission will be depending on the material properties (μ/ρ) and its thickness x. The coefficient μ is basically depending on three phenomena: photoelectric effect, coherent and incoherent scattering (Compton effect), and electron-positron pair and triplet production effect. The influence of mentioned effects on the final μ value is very much depending on the radiation energy. In lower energy ranges of the X-ray beam, the μ coefficient will mainly be affected by the photoelectric effect. For higher energies the influence of Compton effect becomes more significant. Finally, the pair production is typical for the highest energy levels. Consequently, the final μ coefficient will be a function of radiation energy in addition to the other mentioned properties like material density and thickness. This function is very individual for different materials and can be used for identifying differences of materials having similar density and thickness. It requires, however, applying of different X-ray energy sources to recognise the coefficient function.

X-ray transmission analysis (XRT) provides a new powerful tool for complex particle description. Separation examples are given on Figures 4, where XRT system is employed to separate coal and tungsten ore. In this case, the valuable information about the internal particle structure is of critical importance to calculate ratio between the impurities and the material of interests. For coal separation, the exact percentage of the rock contamination (shown by green and blue colour) can be calculated and each coal particle (orange) and can further be defined as waste or product for the separation process. For the tungsten ore, each particle can be evaluated in terms of tungsten compound content shown by black colour against the regular rock material (green).

This information from the XRT system can easily be combined with the image processing employing texture analysis to recognize other objects contaminating our valuable materials. Separation of coal from rock impurities, metal pieces and wood particles can be an example of such advanced separation.

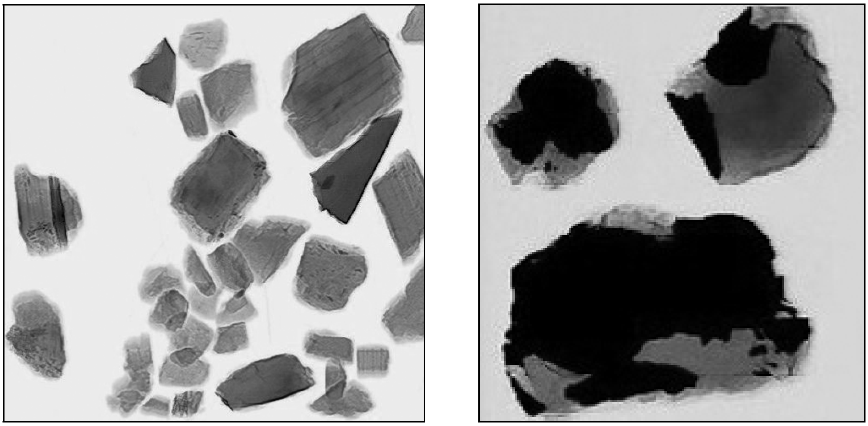

Fig. 4. Separation of coal (left) using XRT analysis.
Green and blue areas show contaminating rock particles.
On the right — separation of tungsten. Black areas represent tungsten compounds

4. Advanced filtration tools

Images which are digitized can be further processed by a variety of digital filters which can provide very advanced analysis. Normally the digitized image is processed by analysing each pixel and setting up a number of thresholds for the light intensity in different colour planes. This method, however, provides a limited particle structure analysis when a particle has uneven lighting or has an irregular form with many surfaces positioned at different angles. This provides reflections which further disturb the important information. This problem can be solved when the frequency filtration is applied. Frequency filters alter pixel values with respect to the periodicity and spatial distribution of the variations in light intensity in the image. Frequency representation is obtained through a function called the Fast Fourier transform (FFT). The spatial frequencies seen in an FFT image can be filtered (low pass or high pass filter) and the inverse FFT then restores a spatial representation of the filtered FFT image as shown on Figure 5.

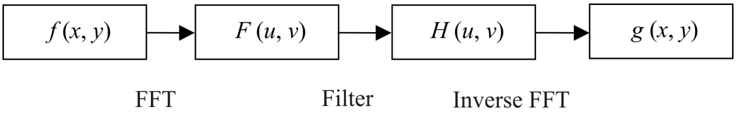

Fig. 5. Illustration of the FFT filtration

The $f(x, y)$ is the light intensity of the point (x, y) and (u, v) are the horizontal and vertical spatial frequencies. The FFT transformation is defined as:

$$F\left(u,v\right)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f\left(x,y\right)e-j\cdot 2\cdot\pi\left(xu+yv\right)\mathrm{d}x\mathrm{d}y \tag{2}$$

Inversely, a Fast Fourier Transform *F* (*u*, *v*) can be transformed back into a spatial image *f* (*x*, *y*) as shown below (*N* and *M* define a resolution):

$$f\left(x,y\right)=\sum_{u=0}^{N-1}\sum_{v=0}^{M-1}F\left(u,v\right)e-j\cdot 2\cdot\pi\left(ux/N+vy/M\right) \tag{3}$$

The FFT of an image *F* (*u*, *v*), is a two-dimensional array of complex numbers, or a complex image. It represents the frequencies of occurrence of light-intensity variations in the spatial domain. The low frequencies (*u*, *v*) correspond to smooth and gradual intensity variations found in the overall patterns of the source image. The high frequencies (*u*, *v*) correspond to short-intensity variations found at the edges of objects, around noisy pixels and around details. This allows eliminating of noisy pixels from the image and distinguishing the important details.

The FFT transformation based filter, however, has a significant limitation related to the computation power of the image analysis system. It is therefore necessary to optimize the processing steps to obtain a reasonable response time. It is mainly to balance between the image resolution and FFT filtration, which does not need to be applied to high resolution images. Another optimization method can be related to application of ROI (region of interests), where only parts of an image are processed by the advanced filtration tools. Anyhow, this type of image filtration based on FFT transformation, provides a new dimension in the analysing techniques.

5. Rejection mechanism control

During optical sorting, many particles can be rejected simultaneously and at the same time many new particles can be analysed and defined for rejection. Consequently, this creates an additional difficulty for the electronic control system where the CPU has to control many events which are taking place at the same time. In the new Comex optical separators, a part of functions related to rejection control are separated from the main computing device and replaced by FPGA hardware (field-programmable gate array).

FPGA is a field-programmable gate array is a semiconductor device containing programmable logic components called “logic blocks”, and programmable interconnects. Logic blocks can be programmed to perform the function of basic logic gates such as AND, and XOR, or more complex combinational functions such as decoders or simple mathematical functions. In most FPGAs, the logic blocks also include memory elements, which may be simple flip-flops or more complete blocks of memory. A hierarchy of programmable interconnects allows logic blocks to be interconnected as needed by the system designer, somewhat like a one-chip programmable breadboard. Logic blocks and interconnects can be programmed by the designer, after the FPGA is manufactured, to implement any logical function — hence the name "field-programmable".

The main processing unit, based on the CPU, is used to transfer images from the analysing camera, provide a basic analysis, electronic filtration and define coordinates of the particles for rejection together with the time delay for initiating rejecting mechanism (pneumatic nozzles or flaps). This last information related to rejecting function, is further processed in the FPGA hardware as shown on Figure 6.

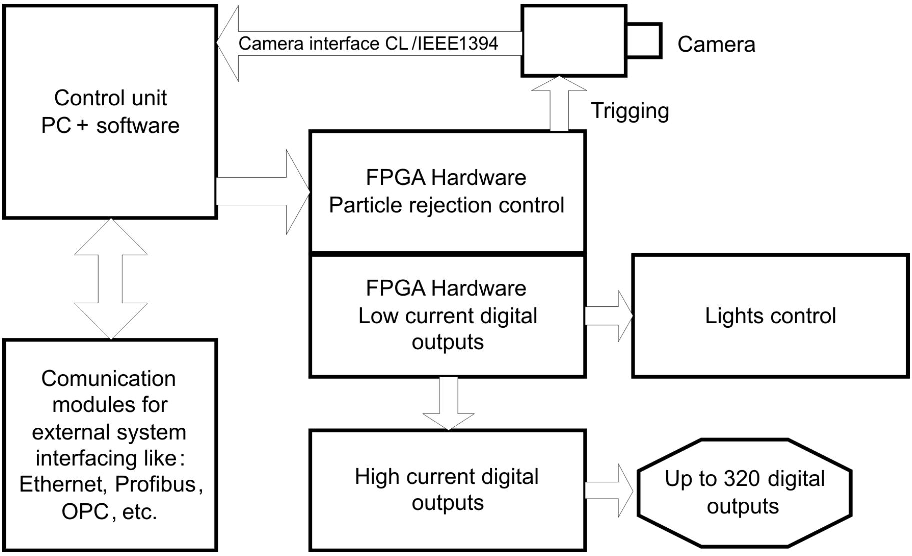

Fig. 6. Illustration of the optical sorting system architecture employing the FPGA technology

This allows the rejecting function to be totally separated from the main CPU operation. In the FPGA area, the program related to rejecting of particles is 'burned' in permanently or semi-permanently as part of a board assembly process, or is loaded from an external memory each time the device is powered up. The main CPU device is not engaged with any activity related to this action and it can therefore be used more accurately with image analysis and electronic filtration. As a result the complete system provides much more precise timing for rejecting waste particles thus improving the overall system performance.

6. Conclusion

The presented optical sorting system can provide a sophisticated image analysis and efficient separation of minerals having different properties. An imaging system employing different types of cameras can provide additional information including other properties of the processed mineral like: shape, colour, size, thermal and magnetic properties, X-ray attenuation and chemical properties. This gives much higher range of possibilities for new separation criteria in mineral sorting. The optical system employs the latest state-of-the-art electronic components including high definition cameras at the system input and programmable gate arrays (FPGA) for the rejecting mechanisms. This provides significant improvements when compared to earlier technologies available on the market.

Separating systems based on image analysis must always be tailored for the particular application. Additionally, efficient separation of materials often requires multiple parallel processing with many sampling points (cameras). The newly developed sorting system gains with both high flexibility and the low cost of the processing unit. This is of critical importance to provide an efficient and complex system, being not cost prohibitive for demanding industrial applications.

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