DEVELOPMENT OF ADVANCED IMAGING TECHNIQUES FOR REAL TIME PARTICLE SENSING IN MINERAL PROCESSING AND RECYCLING

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ABSTRACT

With the ever increasing pressure for digitization and optimization of mineral processing operations, there is a growing need for real-time monitoring solutions providing informations about individual particles and their nature. This paper briefly reviews existing on-stream analytical techniques and stresses the need for "single particle sensing systems". A series of technologies developed at ULiège, GeMMe, are presented together with a small case study.

1 Current Practice in Monitoring of unit processes

1.1 Online technologies (Bulk Particle Sensing – BPS)

The very first online control systems were introduced in the mineral processing industry in the sixties. By the time, they did not form an integrated system but rather assisted in the control of specific units. They typically provided measurements of the pulp level and solid concentration and were essentially used to regulate the slurry flow. In the eighties, basic regulation loops were already implemented in many plants around the world, but integrated plant control really started in the nineties when all data generated by sensors were gathered into a plant-wide control system. From there on, data were continuously recorded and stored enabling the emergence of day-to-day plant management through data reconciliation (Sbarbaro and Del Vilar, 2010).

With the development of process instrumentation, two different control strategies were implemented in parallel (Hales, et al. 2009): expert systems and model-based predictive control systems. Expert systems tend to model the action of expert operators, they are based on algebraic decisions and can prevent any deviation by monitoring a set of controlled points. These simple systems have been widely adopted by the mining industry since the seventies. Nowadays, these systems are typically known as supervisory control and data acquisition (SCADA) systems. On another hand, model-based predictive control systems were initially based on the modelling of the unit processes, before later modelling the plant process as a whole. Hybrid systems have progressively emerged with the integration of simple models into expert systems. The adaptability of these control strategies inherently limited by the accuracy of the predictive models. Hence, predictive models have been the focus of much attention since they are important both for process operation and for plant design.

As already stated, the efficiency of any system is limited by the quality and the relevance of the data provided by the instruments. For long, instruments providing data on the quality of the ore were simply non-existent. Today, a series online/on-stream analysers are commercially available.

Ultrasonic attenuation measurements have been available since 1971. They have been progressively improved and installed in many processing plant. Typically they provide five classes of particle size in slurries with up to sixty percent solids (Wills, 2005; Coghill et al., 2002).

More recently, systems based on laser diffraction have been developed in partnership between Malvern and Outotec (Kongas et al., 2003) and are running in a significant number of plants, although no commercial statistics are available to the authors. This technology has the advantage of providing more details about the fine fraction in the particle size distribution. Remes et al. (2010) described an interesting case study where an on-line laser diffraction based system is used as an input variable for the control of an apatite grinding circuit. The installation of such system was also reported in an iron ore plant. Finally, a system based on focussed beam reflectance has been reported for flocculation control (Kumar et al. 2013).

Systems for on-line control of ore grades were developed in the beginning of the sixties (Wills, 2015). These systems were based on X-Ray Fluorescence (XRF) and underwent significant improvements in the early eighties. Two different approaches can be distinguished: - either centralised on-stream analysers, which employ a single high-energy excitation source for analysis of several slurry samples delivered to a central location; - or decentralised in-stream analysers which use multiple smaller sensors installed at specific points along the circuit. These last systems make use of a lower energy X-Ray source. Centralised analysis is usually installed in large plants, requiring continuous monitoring of many different pulp streams, whereas smaller plants with fewer streams often incorporate individual probes representing a lower capital investment (Wills, 2015). A typical example of a centralized system is the one developed by Outotec, called the Courier 300 analysis system (Koskinen et al., 1973).

The major limitation of XRF based systems is that they are unable to quantify light elements. This issue can be partially overcome by the use of LIBS or Laser Induced Breakdown Spectroscopy (Barrette and Turmel, 2001) However, LIBS systems induce higher maintenance costs and are still under development. They have only found a few very specific niche applications in the industry.

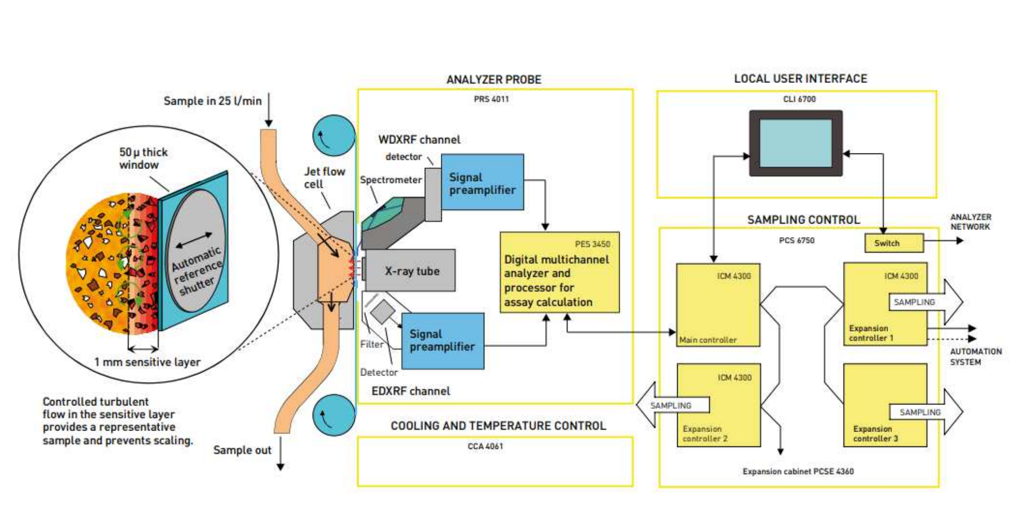

Figure 1: A centralized on-stream analyser © Outotec Courier 5i.

Despite the development of more effective on-stream chemical analysers, it is important to bear in mind that elemental grades are often not relevant indicators of mineral grades. Therefore, several authors have attempted to develop sensors based on mineral characteristics, especially in flotation circuits. For example, the use of visible and near infrared light (VNIR : 400 - 1000 nm) combined with on-stream XRF has proven successful to obtain a more robust and accurate prediction of grades in a copper – zinc flotation plant at Pyhäjärvi, central Finland (Haavisto and Hyötyniemi, 2011). The essential benefit of using VNIR spectroscopy as opposed to XRF analysis is the possibility to conduct instantaneous measures at very regular intervals (5 to 10 secs), whereas XRF typically needs 10 to 20 min. Figure 2 illustrates the principle of the VNIR analyser used in Pyhäjärvi plant. The jet flow cell is a proprietary analytical cell from Outotec designed to ensure intensive stirring of the pulp and improve the representativeness of the measurement.

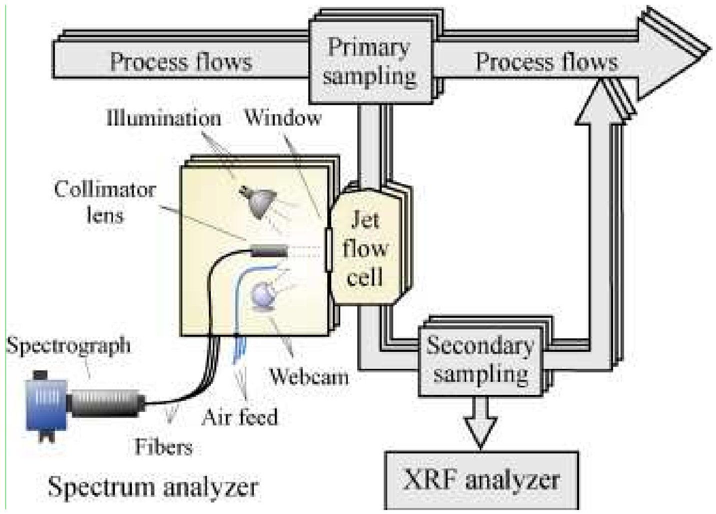

Figure 2: Example of a VNIR spectrum analyser prototype installed directly on the primary sample flows of the XRF analyser (Haavisto and Hyötyniemi, 2011).

The VNIR reflectance spectrum of the slurry is measured through a window in the jet flow cell. A halogen lamp is used for illumination and an optical fibre fitted with a collimator lens guides the light beam towards a prism-grating-prism spectrograph (Specim ImSpector V10) equipped with an ordinary grayscale camera (Haavisto and Hyötyniemi, 2011).

More recently an online time-resolved Raman technology was introduced (Tanskanen et al., 2017) and demonstrated promising results in monitoring and quantifying mineral abundances (talc, magnesite, spodumene,…) in slurrys. An added benefit is that this same technology can be used in high-temperature applications.

1.2 On site and off site technologies

Besides on line or on stream technologies a whole range of sensing techniques are available on site provided samples can be systematically or even automatically sampled. This is the case for all analytical chemistry instruments (XRF, ICP-MS,…) and also for a whole range of particle size analysis instruments using mechanical, electrical or optical sensing principles. See Hart el al. (2011) for a review.

It is important to realize that, with the exception of imaging microscopy, most of these techniques measure the characteristics of a particle flow and as such are bulk particle sensing techniques (XRF, laser diffraction, etc.). Single particle sensing is only possible with techniques such as the electrical sensing zone (Coulter counter), but most often require imaging microscopy to be able to measure size and shape of individual particles.

Imaging microscopy be it in visible light or using scanning electron beams is also the technique of choice to access mineralogical information. It has been widely used since more than thirty years to provide a unique insight into the mineralogical liberation of particles and is the only tool capable of providing a mineralogical balance and a visualisation of the elemental deportment within a given process. The main limitations are linked to sensitive sample preparations; the necessity to hire expert mineralogists and the consequently long to very long time delays (from several hours to several days).

2 Advanced Needs in Monitoring of Unit Processes

Future instruments will have to tackle the following challenges if they want to bring innovation to the market:

A need for speed:

- No sampling or eventually automatic sampling without stopping the process
- No sample preparation or eventually a limited dilution / dispersion step

A need for instruments capable of imaging and analysing individual particles (Single Particle Sensing - SPS). These can be categorized based on the following constraints:

Imaging capabilities for particle streams with extended particle size ranges:

- 1µm - 200 µm : non-free flowing powders requiring magnifications of 100x to 1000x
- 200 µm – 5 mm : free flowing powders requiring macroscopic imaging of 0,1x to10 x

Imaging capabilities for variable material throughputs:

- High throughputs requiring bulk imaging followed by digital particle segmentation
- Lower throughputs which can be imaged by dispersion followed by image thresholding

Imaging capabilities for wet or dry particle streams:

- Dry : mechanical dispersion of free flowing particles in air
- Dry : mechanical dispersion of non-free flowing particles using vacuum
- Wet : Mechanical dilution of fine particles in water (pulp)

Imaging of dynamic streams of particles, with two distinct configurations:

- Static Image Analysis (SIA) where particles are only translated within the imaging plane (no rotation or out of plan movement).
- Dynamic Image Analysis (DIA) where particles might rotate with respect to the imaging plane (random orientation and eventually out of focus movements)

3 Particle Sensing Technologies for Real Time Applications

The following paragraphs illustrate some recent technological developments made within the GeMMe group of ULiège and addressing the needs for single particle sensing in real-time for different applications and different particle size ranges.

3.1 PULPMIN

3.1.1 Imaging principle

Pulpmin is a single particle imaging system aiming at measuring the size, shape and indicative mineralogy of fine particles (1 µm – 100 µm) in pulp. It has been developed to identify base-metal sulphide minerals, from the measurement of specular-like reflections on the surface of particles. The system is based on an original lighting and imaging set-up to avoid optical aberrations and parasitic reflections that would have been observed with a conventional microscope (Leroy and Pirard, 2019).

The core of the system is a camera optimized for low-light conditions. This camera is fitted with an infrared corrected x10 objective lens. The pixel resolution corresponds to 1.6 µm/pixel. In practice, considering diffraction artefacts and the resolution needed for accurate identification, the system is adequate for particles which have a minimum width of 20 pixels (30 µm).

The lens focusses inside a flow cell, which consists of a 500 µm high parallelepiped space limited by a top and a bottom glass window. The two glass windows are held together by a metallic frame. The system further includes a multispectral lighting source and a peristaltic pump that sucks the pulp into the flow cell. The cell is positioned in such a way that its two glass walls are horizontal. The camera and the lighting system are placed below the cell, perpendicular to the lower glass window. A white LED is placed above the cell in the optical axis of the camera. Images are taken when the flow is still and particles are settled in the focus plane of the objective. An overview of the system is shown in figure 3.

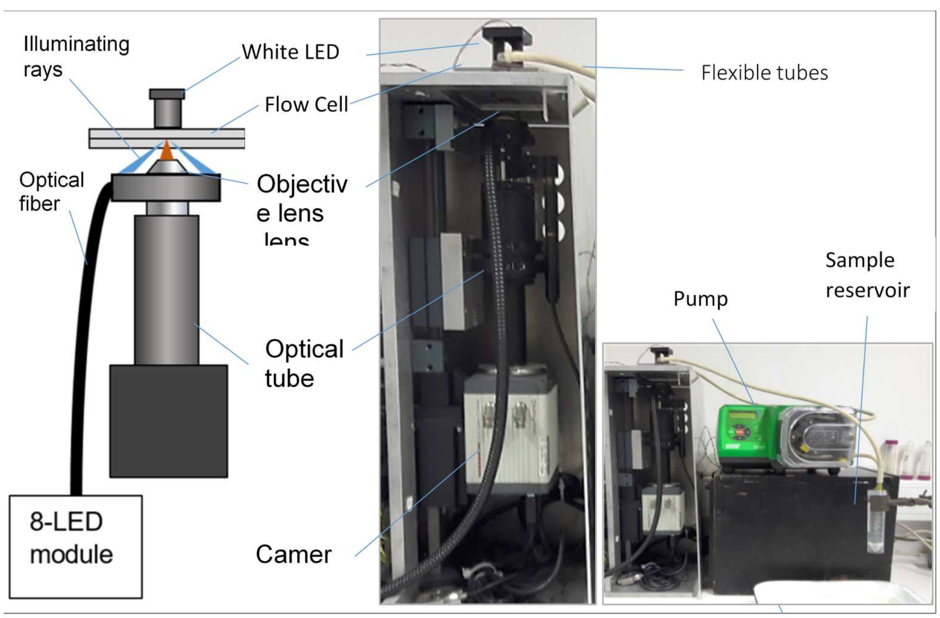

Figure 3 – Left: sketch of the imaging set up. Middle: picture of the system, focus on the imaging part. Right: overview of the set-up

The lighting equipment is made of a series of eight narrow-waveband LEDs at 405 nm, 455 nm, 530 nm, 590nm, 617 nm, 735 nm, 850 nm and 940 nm. The LEDs are collimated and assembled with a series of dichroic mirrors in such a way that all light rays follow the same exit path. An optical fibre is used to conduct the light from this exit path into a diffusing ring placed around the objective lens.

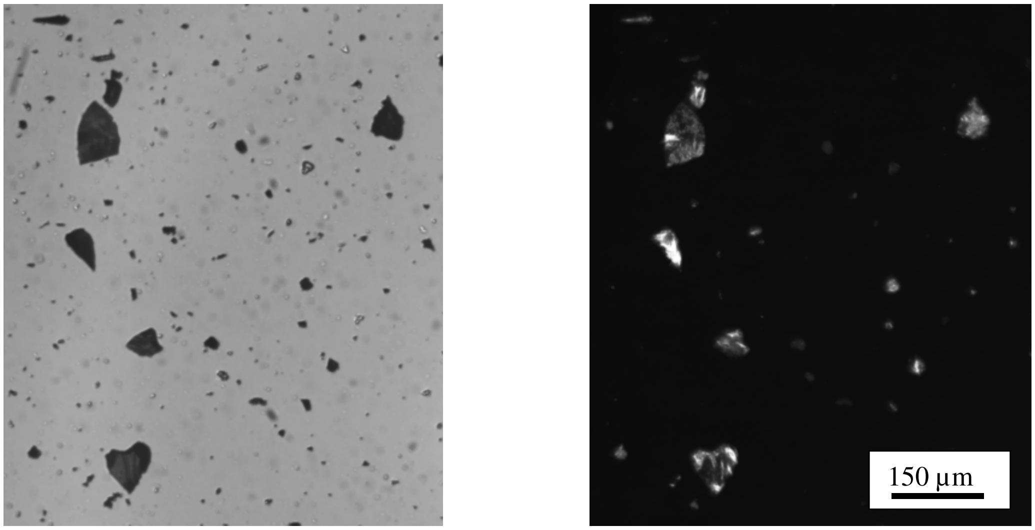

Figure 4 – Left) Transmitted (diascopic) image of the same scene; Right) Reflectance (episcopic) image at 405 nm;

3.1.2 Case study

A series of samples were prepared by mixing pure minerals in known proportions. Individual minerals were ground down to 95% passing 150 µm, assayed and characterized by XRD and optical microscopy to check their purity (found to be between 90% and 99%). The samples were suspended in demineralized water for pumping and imaging with the flow cell instrument.

At each sampling interval, the system took pictures of the particle flow: first a transmitted black and white image and second a multispectral image using the sequential illumination of the different diodes (Figure 4). The first image is used to create a mask and help identifying pixels belonging to the same particle in the multispectral image, it also serves to identify gangue (translucent) particles (Leroy et al., 2011).

To validate the technology, the system was trained on particles of known mineralogy and a random set of pixels (5%) as taken on each mineral present in the mix. Based on the statistical features of these random sets, images are further classified using linear discrimination analaysis of feed-forward neural networks. See Leroy and Pirard (2019) for more details.

The reflectance properties of individual minerals are clearly affected by the irregular surface topography of individual particles. Most particles display shadowing effects or bright specular spots that might hinder the efficiency of the pixel-based classification process. However, as can be seen in figure 5, the median spectral profiles show very clear trends and open the way for automated discrimination. The system has been validated on various samples including binary and ternary mixes. Figure 6 shows the result of neural network classification on a mix of four minerals.

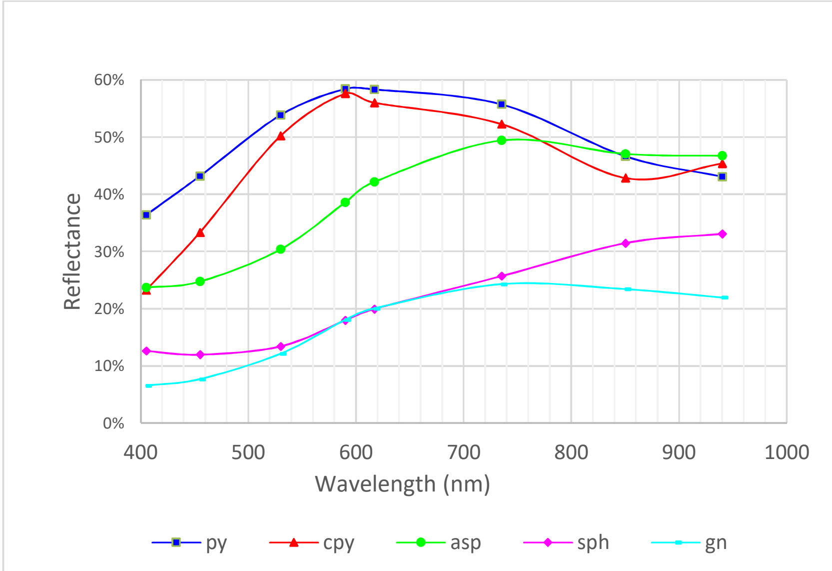

Figure 5 – Spectra of median reflectance values for five major sulphide species in real time pulp imaging conditions : Pyrite (Py); Chalcopyrite (Cpy); Arsenopyrite (Asp); Sphalerite (Sph) and Galena (Gn).

	Py – C	Cpy – D	Asp - E	Sph – F	Results visualisation
Py – C	0.61	0.13	0.22	0.03	
Cpy – D	0.03	0.89	0.07	0.01	
Asp - E	0.06	0.01	0.87	0.06	
Sph – F	0.17	0.02	0.08	0.88	

Figure 6 – Matrix of confusion resulting from neural network classification of a mix of pyrite (Py - blue); Chalcopyrite (Cpy - red); Arsenopyrite (Asp - green) and Sphalerite (Sph - purple) fine particles (100 µm).

3.2 LaserSieve

3.2.1 Imaging principle

LaserSieve is a non-invasive and non-disruptive online 3D measurement system developed by ULiège (GeMMe) and industrialized by Metheore sprl. This system provides the size, shape as well as throughput measurements of the bulk solids moving on a conveyor belt in real time (Dislaire et al., 2012). The system is efficient and robust enough to operate in harsh industrial environmental conditions. The system can also be integrated with the industrial equipment like crushers, mills, etc. to regulate them directly for automatic mitigations of any disturbances.

LaserSieve is integrated with a web-based application to monitor the data remotely using a PC or a smartphone. The system uses a combination of a laser and a high-resolution line scan camera, connected to a processor, which enables it to take 30000 profiles/second and analyse the material on a conveyor belt running up to a speed of 3.2 meters/second with an accurate spatial resolution of 0.92 mm. Unlike similar systems which suffer due to computation or processing limitations and are only able to capture data at specific intervals, LaserSieve analyses the totality of the visible material flow.

LaserSieve is based on the principle of laser triangulation which converts the image of a broken line into a height profile given the known characteristics of the triangle linking the sensor, the laser light sheet and the conveyor position (Fig. 6). The result is a 3D range image (surfometric image) wherein grey values are directly relate to distances to the sensor (Thurley, 2011).

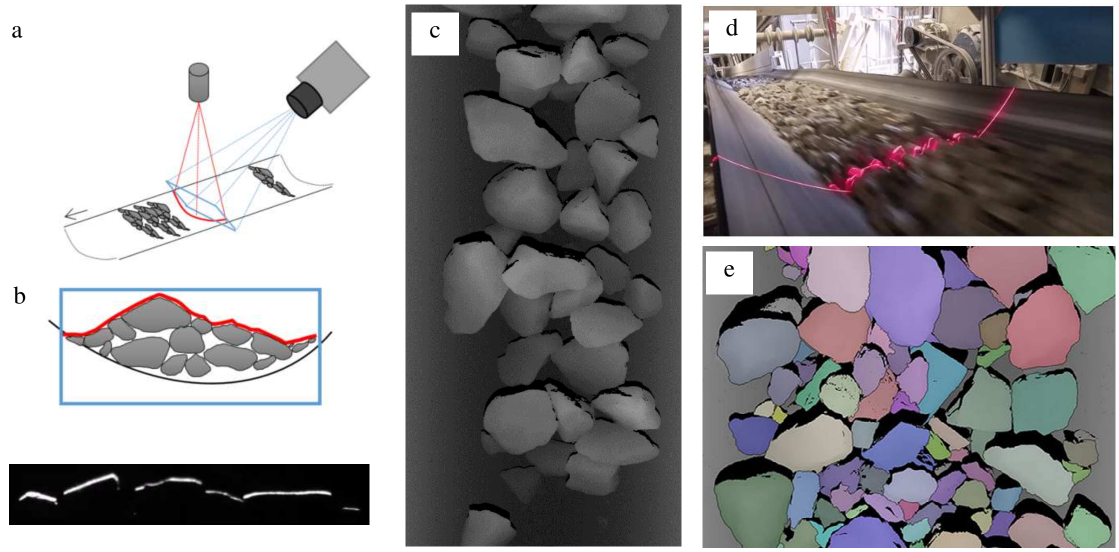

Figure 6 – Principles of the LaserSieve single particle imaging system: a) Projection of a laser light sheet onto the conveyor and realtime imaging with a range camera (Sick IVP); b) Section of the conveyor belt with captured profil; c) real time surfometric image resulting from a thousand linescans; d) view of the system in operational conditions; e) post-processing to outline invididual particles/agregates.

3.2.2 Case Study

Plant scale tests have been designed and performed for several weeks in an operating industrial environment to evaluate opportunities for optimization. The primary focus of the tests has been to monitor the primary jaw crusher and cross-check the results provided by the LaserSieve system with continuous belt scale measurements (for throughput) and manual screening (for particle size distribution). These tests did not require any special sample preparation and were conducted during the normal operations of the plant. Figure 7 illustrates the impact of changing the closed side setting of the primary crusher from 175 mm down to 143 mm and looking at the different percentiles of the particle size distribution in real time.

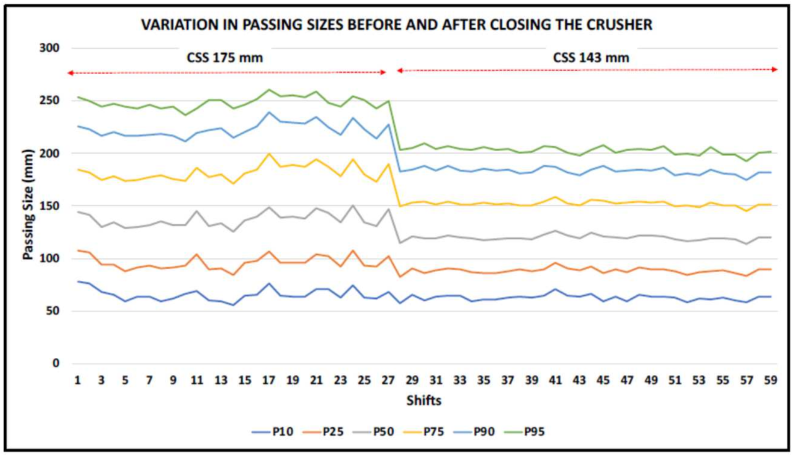

Figure 7 – Real-time monitoring of the impact of operational conditions on the output of a primary crusher with the LaserSieve system.

3.3 Iliad

3.3.1 Imaging principle

Iliad is a system designed to analyse the diffuse reflectance of particles in the millimetre range. It uses a vibrating tray and a conveyor belt to disperse individual particles mechanically in the imaging plane. The imaging system is made of two line scan cameras sharing the same optical axis. Barnabé et al. 2015 describe the design of the instrument and the necessary calibration steps to be able to merge the VNIR line (400nm-1000nm, CMOS, 1300 pixels/line) with the SWIR line (970nm-2500nm, MCT, 320 pixels/line). Although the system would be optimal to identify different lithologies / mineralogies thanks to its extension into the SWIR range, it has been designed primarily to address the needs of quality control of metal concentrates in recycling operations (figure 8). A further prototype includes a small-scale laser triangulation system to estimate the volume of individual particles and give a better estimate of weight proportions.

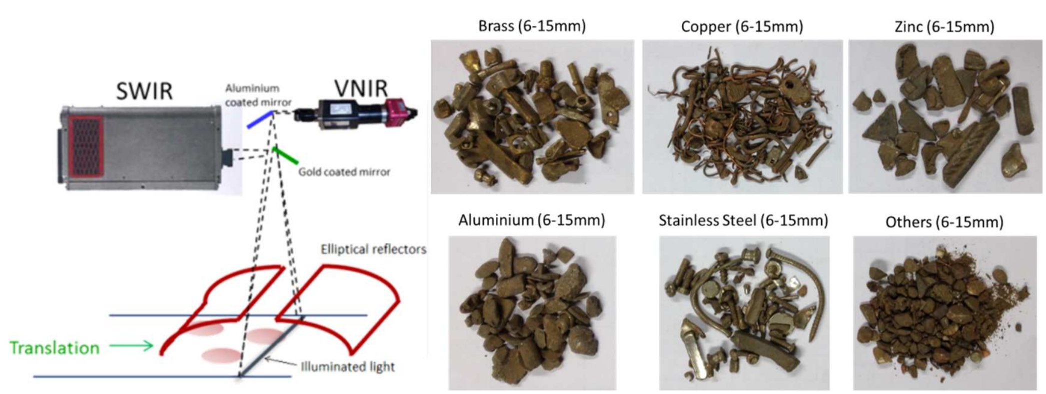

Figure 7 – Sketch of the ILIAD imaging system showing a SWIR (Specim Oy) and a VNIR (PhotonfocusMV1+ImSpector V10E) linescan camera sharing the same co-axial optics. Sample specimens of 6 mm to 15 mm scraps from various metal categories used to train the imaging system.

3.3.2 Case Study

A dataset, containing 100 fragments previously sorted with portable XRF (20 fragments per class, five distinct materials classes) (fig.7), has been imaged with the ILIAD system. Pixel spectra have been collected and submitted to different machine learning tools. Best results have been achieved using the Random Forest algorithm applied on features extracted with Linear Discrimination Analysis (LDA). The resulting confusion matrix indicates an average correct pixel-based classification of 92% with copper reaching a 99% rate, while brass is down to 82%, due to a 10% confusion with the stainless steel category. Although improvements in imaging can still be expected, the main cause of misclassification is probably linked to surface tarnishing (fig. 8).

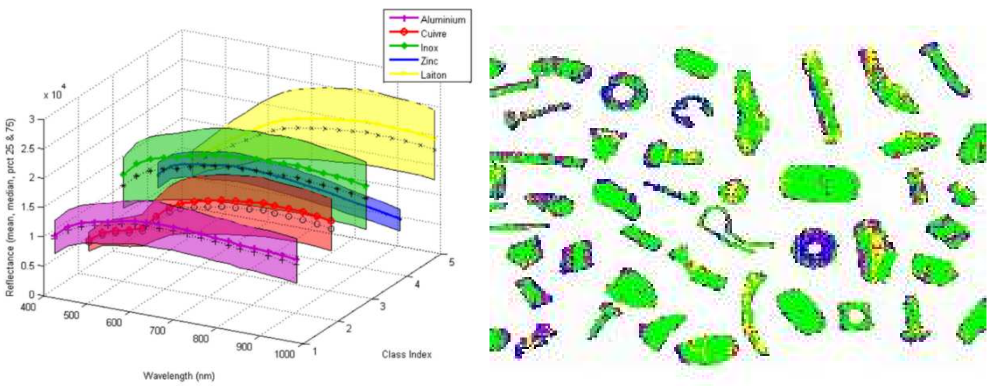

Figure 8 – Range of spectral distributions (Q_1-Q_3) of the different scrap types in the VNIR range and pixel-based classification of stainless steel particles showing 86% positive and partial confusion with brass, zinc and copper.

4 Conclusions

Multisensor imaging techniques are reaching maturity and can be considered for a wide range of applications in primary and secondary resources characterization. These same technologies can help to develop quality control instruments as well as advanced optical sorting systems. The main advantage is that no sample preparation is required which means that real-time online / on stream imaging is possible and delivers accurate information within time delays required for automatic regulation. With a better understanding of unit processes, it will hopefully be possible to move from feedback control systems (acting a posteriori) to feedforward control systems (acting a priori).

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