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Review article

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DEVELOPMENTS AND APPLICATIONS OF 3D IMAGING SYSTEMS IN MINERAL PROCESSING

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Abstract

Three-dimensional (3D) surface imaging systems have gained popularity in monitoring the status and condition of separation processes by characterizing the internal and external structures of particles such as size, shape, density and composition. This review article mainly focuses on demonstrating the state of the art of 3D imaging systems in mineral processing based of the recent growth in 3D sensors. The structure of this manuscript comprises an overview of the two 3D imaging systems, including RhoVol and X-ray computed tomography, based on the basic principles. Their applications in mineral processing are then explained. By integrating with other imaging tools and the 3D printing technology, 3D surface imaging systems will play an important role in the automation and control of mineral processing in the future.

Key words: *3D sensors, mineral processing, RhoVol, computed X-ray tomography, automation.*

1. Introduction

Technological advances like GPUs (Graphics Processing Units), high speed cameras and the rapid development of artificial intelligence have resulted in a revolution in the development of machines or tools that may be used in mining [1–4]. With the development of technologies, the capability of computer vision technology has been significantly developed, so that the automation technology based on computer vision systems is becoming a vital part of mining industries to improve productivity and efficiency. In the past few years, vision systems have become the key sensors in mineral processing operations [2, 5–8], and their use has rapidly increased. These systems are fast, non-invasive and cost-effective and are widely used in many separation applications such as comminution, classification and flotation [9–12].

A better understanding of particle behavior in the separation processes relies on the assessment of particle shape. Two-dimensional (2-D) vision technologies have been an important part of the effective application of mineral processing automation and control. Traditional 2D techniques should be complemented by innovative image sensing and improved by data analysis methods to accelerate the increase in mineral processing productivity in a more accurate manner. It has commonly been assumed that the computer vision system is at an inflection point, moving into a three-dimensional (3D) method, driven by the advanced imaging systems [13]. Although the 3D images processing needs high-performance computing technology and is costly, computationally complicated, and time-consuming, there has been a growing initiative to create 3D imaging systems to enhance the understanding of how granular materials behave in the process [14, 15].

In the last decade, with the development of new computer technologies, the number of publications on the successful implementation of the three-dimensional (3D) imaging systems in mineral processing has been growing fast [16–18].

3D measurement methods are becoming increasingly important, because they can provide the accurate analysis of complicated morphologies of particles and 3D spatial distribution, simultaneously. Recent advances in 3D imaging techniques not only open a new window to substitute new identification methods, but also have the potential to alleviate some common errors in traditional methods. From mining to grinding operations, the 3D characterization of particles ranging in

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size from meters to micron is currently feasible. Spatial particle features, such as size, shape, and composition, are fundamental features that can determine the productivity of the plant operations in the mining industries. 3D imaging systems will be gradually used in the field of mineral processing automation and will steadily promote the development of mineral processing operations to the era of intelligent mining 4.0. Currently, several techniques have been introduced to capture the 3D particle geometries by various 3D imaging systems, including RhoVol, stereo photography, X-ray CT, 3D laser scanning, white light scanning [19–22]. Some application of 3D imaging techniques in mineral processing is summarized as follows (Table 1):

Table 1 Application of 3D imaging techniques in mineral processing

Feature	Reference
Morphological characterization and quantification (size and shape)	[23, 24]
Determination of microstructural features such as:	
- crack density, rock characteristics	[25, 26]
- intergranular fracture and crack surface area during multiphase particle breakage in comminution operations	[27, 28]
Quantitative characterization of pore size and structural features	[29]
- Mineral liberation and grade grade-recovery curves	[17, 30, 31]
- Exposed grain surface area	[32, 33]
Density	[16, 22]

This paper summarizes the publications and findings from 2015 to 2023 regarding the advances and applications of 3D imaging technology in the field of mineral processing. The existing technologies, such as high-speed scanning and image analysis techniques to measure significant particle characteristics, such as size, shape, volume, density and composition are introduced. Future opportunities and prospects are also described to develop a current reference for researchers. This review presents the application of 3D imaging techniques such as RhoVol and X-ray tomography along with their information in the mineral processing.

2. 3D imaging systems

2.1. RhoVol

The primary approach for visually recognizing particle shape was developed by Krumbein [34] in which the morphologies of the particles can be characterized by the sphericity and roundness factors derived from 2D projections [35–37]. This technique relies only on the comparison of visual images of particles by microscopic assessment, without any image processing (Figure 1). The main weaknesses of this approach are that it is tedious and time-consuming, the results depend on the user experience, and it is limited to large-sized particles [38]. Although image-based methods have been employed to evaluate particle shape through 2D projections, the restrictions of 2D projections have motivated researchers to improve 3D imaging systems to better measure particle characterizations [39].

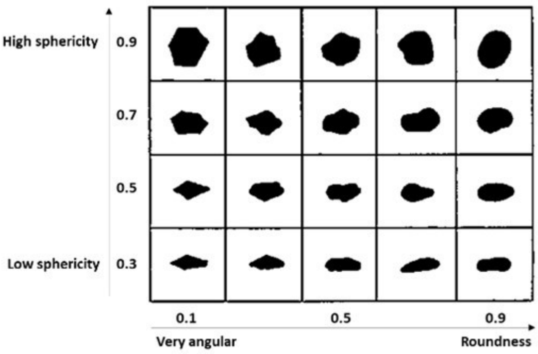


Figure 1 Classification chart based on roundness and sphericity of particles [35–37]

State-of-the-art advances in imaging systems can produce external geometry of particles into 3D models that can be employed to determine key descriptors of particle morphology such as the values of length, diameter, perimeter and volume.

The RhoVol machine, commercially developed by De Beers Group Technology, measures and records the mass of each particle, followed by a 3D reconstruction of its silhouette [18]. It was initially developed for analysing diamond characterizations, but was later promoted for other applications, such as coal. The RhoVol uses seven cameras at various angles to capture seven silhouettes of a particle at a time (Figure 2). There are three types of RhoVol machines for measuring the properties of fine (-3+1 mm), medium (-8+3 mm) and coarse (-8+25 mm) particles.

RhoVol's software produces a 3D model of a particle by merging integrated information, so that any physical dimension or ratio can be extracted such as density (mass/volume), size, elongation, flatness, compactness, and volume of a given particle. It is also equipped with a sorting functionality (twelve containers) that allows the particles to be separated into specific bins on the basis of any designated particle characteristics.

Figure 3 shows the RhoVol system. The feed distribution system consists of two feeders that transfer the samples from the funnel to the weighing system. The weighing system uses a high-speed load cell to accurately measure the mass of each particle. Laser sensors adjust single-particle movement. Once the mass has been measured, the chute gate opens, and the particle descends through a set of seven cameras, generating a 3D image. Sorting is done by a program that can sort the particles based on any particle characteristics selected by the operator, including volume, mass, density, size and various shape features. All parameters except mass were calculated directly from the 3D images. A moving funnel finds the most suitable bin, and the particle then falls into the bin [16, 18].

Figure 4 and Table 2 show the multiple simultaneous views and the results of geometry calculations of a particle using multiple cameras, respectively.

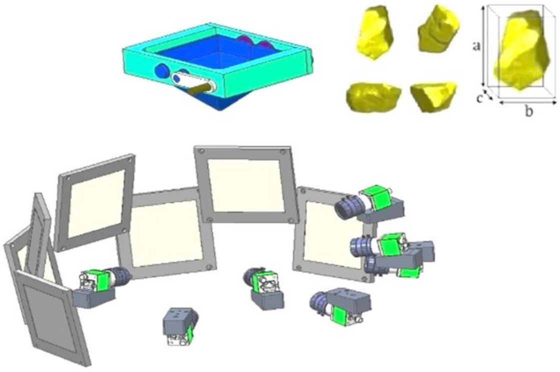


Figure 2 A generated 3D model of a particle using seven cameras [16]

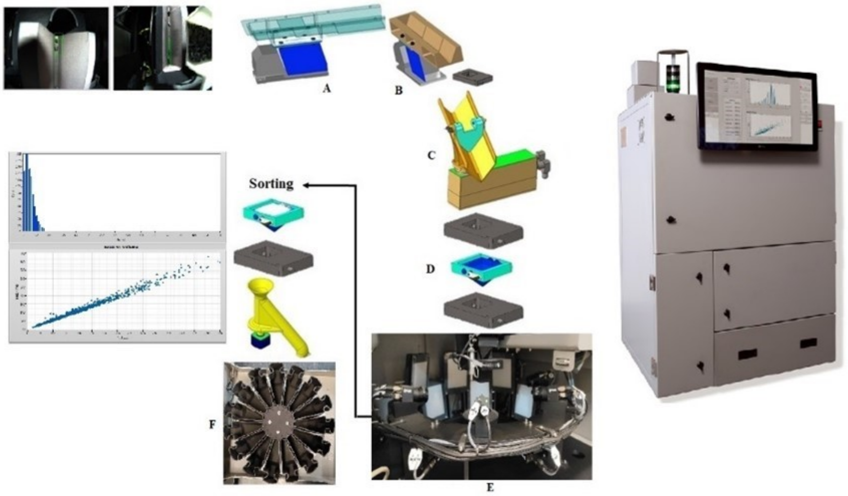


Figure 3 The RhoVol machine [22]. (A) and (B) primary and secondary feeders, (C) weighing system, (D) sampling chute, (E) cameras and (F) bins [16]

Figure 4 The multiple simultaneous views of a particle using RhoVol [16]

Table 2 Particle geometry results of a coal particle shown in Figure 4 [16]

Particle	Volume	Minimum circle diameter	Elongation	Flatness	Compactness	Minimum square sieve size	Roller gap size
	(mm^3)	(mm)	a/b*	b/c*	(bc/a^2)$^{1/3}$*	(mm^2)**	(mm)
1	32.96	4.12	2.83	1.41	0.45	3.26	2.44

*The length (a), width (b) and thickness (c) are the longest, intermediate and smallest dimension of the minimum bounding box, respectively.

**Minimum square sieve size is explained as the limiting size at which a particle can pass through a square aperture with side dimension.

Botlhoko et al. [16] compared the particle size distributions (PSD) of coal samples obtained by the RhoVol method and by sieving tests. There were only minor differences between the particle size distributions based on sieving and RhoVol results. Therefore, the RhoVol system provides a practical reference to establish the applicability of the 3D image-based method to measure particle size.

Washability analysis is used to ascertain the yield and quality of coal particles. The traditional tedious float-sink experiment is frequently used to study the washability of coal, which defines the ideal separation density for coal cleaning [40, 41]. Coal cleaning is performed to eliminate minerals from raw coal, in order to increase the quality of coal and reduce the emissions of sulfur dioxide from burning coal in power plants [42].

Accurate density measurements are essential for characterizing Run-of-Mine coal, and estimating the coal washing plant's performance [43]. Botlohoko et al. [40] compared the float-sink and RhoVol experiments for to determine the coal washability curves. Since the effect of porosity and cracks on the volume of coal samples is excluded in 3D images, the coal density measurement in RhoVol leads to an overestimation [44]. Therefore, the calculated density based on RhoVol requires some correction factors. A number of techniques like neural networks (NN) and linear regression techniques to address this problem were developed by Nakhaei et al. [22] and Botlohoko et al. [16]. They created the reliable models for the correction and estimation of coal density by RhoVol.

The RhoVol and float -sink results for two coal samples are given in Figure 5. The curves obtained by the RhoVol are in agreement with the float–sink test. However, the amount of required sample is much lower in RhoVol compared to the float-sink experiment. The yield-cumulative ash content results obtained by the RhoVol and float-sink tests are shown in Figure 6. From the similarity between the RhoVol and float-sink test results, it is obvious that 3D imaging approach can determine the washability of any type of coals.

The results obtained with the RhoVol can be used to specify the washability curves of coal without the need to perform float-sink experiments. This saves time and money and decrease the consumption of hazardous chemicals. Unlike the float–sink approach that is executed at a limited density ranges, RhoVol is able to separate coal particles in a wide density range. Consequently, the RhoVol machine is a useful substitute for the sink–float technique.

Comminution is commonly used to liberate valuable particles in an ore, so that they can be separated from the gangue particles in the following separation operations [45]. It can result in modifications to particle shape. Although the particle shape factors of the feed, concentrate, and tailing streams provide information on the recovery of minerals [37, 46], only limited efforts have been made to measure and characterize ground mineral particles [37, 47–49]. Therefore, the particle shape indexes should be investigated experimentally by 3D imaging systems for comminution, classification and physical concentration methods including crushing, grinding, sieving, magnetic separation, electrostatic separation, gravity separation, and flotation.

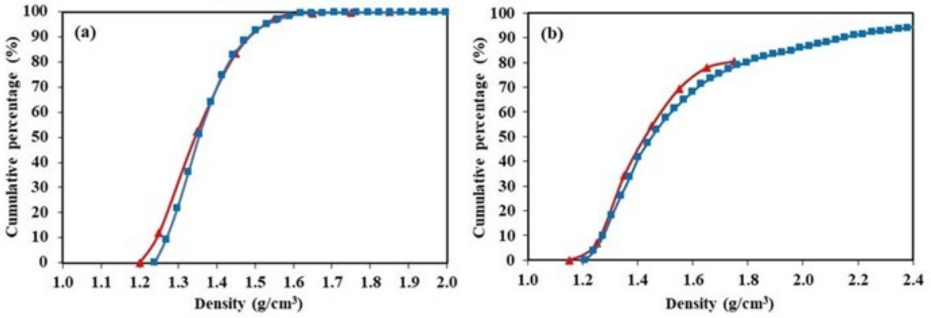


Figure 5 The comparison of the cumulative density distribution obtained by float-sink (red curve) and RhoVol (blue curve) for two samples

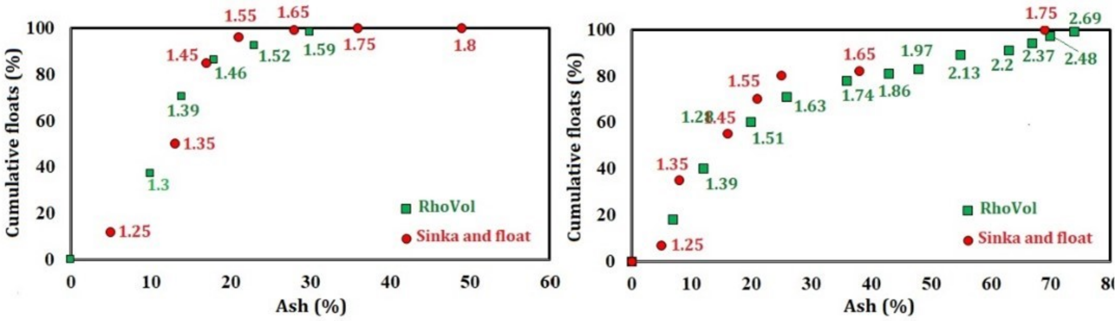


Figure 6 Washability curves achieved by RhoVol (orange curve) and sink–float (blue curve) tests [16]

2.2. X-ray tomography

Recent advances in the wide range of computing technologies and software tools have reached an extraordinary level, so that 3D characterization of multiphase particles is now possible using X-ray tomography. This technology is generally used at airports to inspect baggage during the screening process [50, 51]. This non-destructive quantitative technique is essential for sustainable development and the more effective utilization of valuable mineral resources. The main advantage of X-ray computed tomography (XCT) lies in its ability to capture the 3D internal structure of the ore at resolutions as low as a few microns, thus reducing the stereological inaccuracy obtained via 2D imaging systems [17, 52]. The simplicity of sample preparation and the amount of obtained data available for each individual particle are further reasons for the widespread use of X-ray CT. The size, volume, shape, porosity, and the location of a certain particle in the granular assembly are some of the data that can be extracted from a single scan [14].

Figure 7 shows a simple schematic representation of a typical XCT system. Detailed explanations can be found elsewhere [53, 54], but a brief summary is described here. The specimen is placed upright between the X-ray source and the detector. The maximum energy of the X-ray beam can be varied depending on the X-ray source. The particles are exposed to the incoming X-ray beam which is rotated 180° during data acquisition to create a large number of 2D projections (typically between 500 and 3000 projections) using penetrating X-rays [52]. The attenuation of the intensity is recorded by the detector for each projection image. After reconstruction, these projections form 2D slices of the measured volume. The pixels in the 2D slices maintain spatial information about the original volume elements (voxels) so that the slices can be stacked and rendered to see the 3D volume of the sample [55].

XCT has been used for quantitative analysis of the main factors, such as particle size, shape and composition [14]. Recent advances in XCT have enabled high-speed scanning and image analysis techniques that can determine the characterization of multiphase particles within minutes [37]. Opportunities for plant-site 3D coarse particle characterization with automated high-speed XCT are now possible.

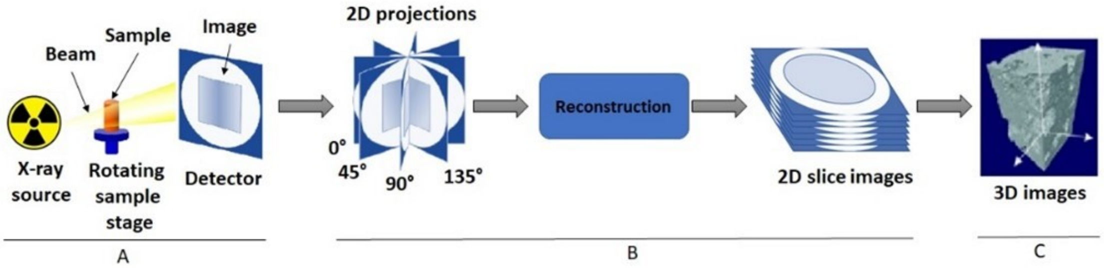


Figure 7 A schematic of a typical XCT workflow. (a) illustration of scanning of the sample including X-ray source, detector and sample, projection images are produced as the sample is rotated; (b) mathematical transformation of the shadow vertical projections into a series of horizontal sections of the sample; (c) produce 3D rendered volume of the sample [56]

Guntoro et al. [55] provided a comprehensive review of the available useful data analysis approaches for processing 3D datasets obtained using a μCT laboratory system as a mineral characterization tool. Micro-computed tomography (μCT) is the latest 3D imaging technique that enables high-resolution analysis of the shape characteristics of particles smaller than a few microns [57, 58].

Liu et al. [59] extensively reviewed the application of XCT on coal characterization. They also explained the imaging principle of CT and the recognition process of microstructure, and summarized the research development of CT in the quantitative characterization of coal microstructures and the qualitative assessment of macroscopic properties.

Several studies have examined the use of X-ray tomography in mineral processing for laboratory analysis. These include (1) multiphase particle characterization [60, 61], (2) particle crack and breakage as a result of blasting/comminution [25, 27], (3) liberation characterization and exposed grain surface area analysis to clarify the liberated particles [30, 32, 62, 63], and (4) floc size, shape, and water content. For example, HRXMT with a resolution of about 5 μm was used toanalyze the mineral liberation of copper feed flotation (+150 μm). The rendered images for this sample are shown in Figure 8.

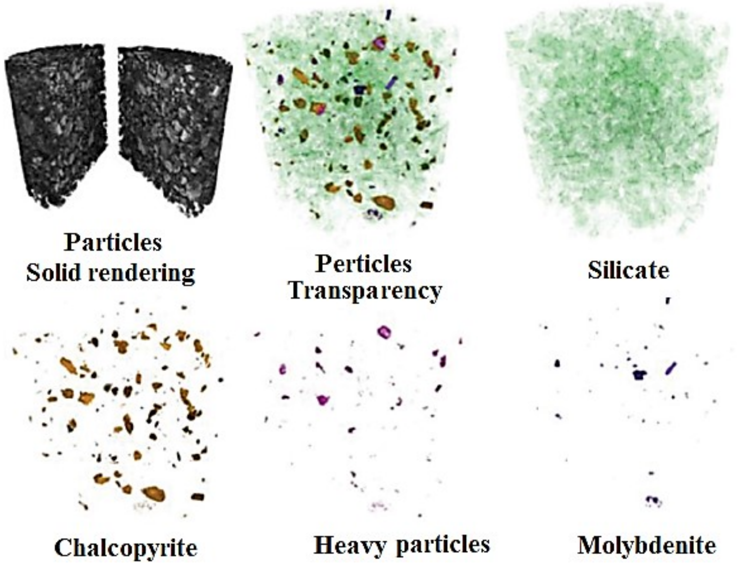


Figure 8 3D images of copper flotation feed (+150 μm) including chalcopyrite; high-density minerals such as covellite, chalcocite and bornite; molybdenum; and gangue minerals obtained by HRXMT (voxel resolution = 5 μm) [64]

It has been stated that some parameters such as surface roughness, heterogeneity, particle shape and size, play a significant role in the floatability of mineral surfaces [65]. The shape of the ground particles plays a significant role in the bubble-particle attachment [66]. Several studies reported that irregular particles have higher flotation recovery and rate, than spherical particles [37, 67–69]. Therefore, selecting the appropriate grinding approach with the proper residence time can improve the flotation separation efficiency. Lastly, it is asserted that the application of 3D imaging systems opens a new window to improve separation processes such as flotation.

Ore sorting is a pre-concentration method used before the main processing line to reduce the amount of gangue minerals from the ores before the grinding circuit. The copper sulfide particles inside the ore were imaged in 3D by micro XCT [70]. If the gangue particles can be detected and removed from the processing line, the remaining particles have a higher feed grade, and thus, the energy cost for following grinding can be considerably reduced. Zhang et al. [71] used dual-Energy X-ray Transmission (DE-XRT) to separate the sulphides from the non-sulphide minerals. The density values obtained by DE-XRT were employed to determine the average atomic density by measuring the X-ray attenuation for each sample. In their experiments, COMEX's MSX-400-VL-XR machine installed at the University of British Columbia was employed (Figure 9).

Figure 9 COMEX's MSX-400-VL-XR System in UBC's Coal and Mineral Processing Laboratory [71]

Figure 10 shows that the DE-XRT sorting method can recover 90% of the sulphides with a 55% mass yield. Moreover, over 95% of the gold equivalent can be recovered in the same amount of mass. It is noteworthy that the calcium recovery rate nearly doubles at a 55% mass yield. This suggests that a higher proportion of carbonates is recovered when 55% of the rock mass is collected in the concentrate. The DE-XRT proves to be a proficient sensor for the effective discrimination of sulfides and gangue minerals.

In another research, Zhang et al. [72] explained the fundamentals of the DE-XRT analysis and its data processing techniques to specify the relative densities and determine the washability curves and density of separation for coal sorting. They showed that similar to float-sink analysis, the DE-XRT can measure relative density by quantifying the attenuation of x-rays from two different energy levels. The coal washability curve derived from the DE-XRT results was able to model washability using sink-and-float test.

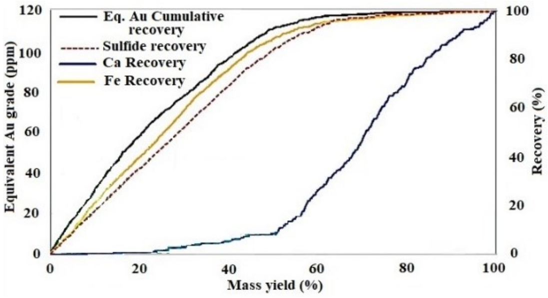
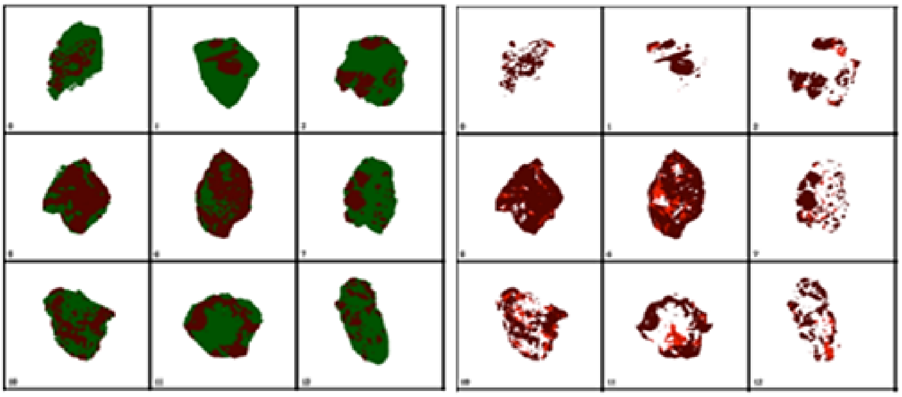
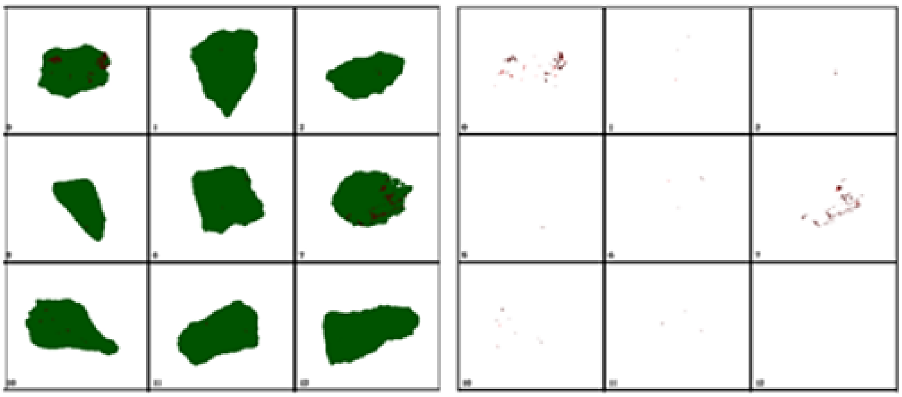


Figure 10 Sortability analysis derived from DE-XRT: Scatter plot of equivalent gold assay versus average relative density [71]

Miller et al. [73] used high-resolution X-ray microtomography (HRXMT) to compare the degree of exposed grain surface required to recover very coarse particles (850×500 μm) using the HydroFloat and mechanical flotation cell. Figure 11 shows the volume-rendered view of the original 3D reconstructed image set (992×1013×790 voxels) obtained with HRXMT for designated particles from the HydroFloat concentrate and tailing. These 3D images perfectly show that little or no exposed grain surfaces of sulfide minerals are present in the HydroFloatTM tailing samples.



Concentrate



Tailing

Figure 11 3D images of 9 particles and exposed surface of 850×500 μm particles of HydroFloat concentrate and tailing (gangue surface = green, exposed valuable mineral surface = red) [32, 73]

3. Conclusion

Advanced technological capabilities of 3D imaging sensors make significant breakthroughs feasible, provided there is ample implementation of research projects. Since the processes of mineral processing are substantially complicated, 3D imaging systems can play a remarkable role in increasing efficiency. The applications include the determination of microstructure, particle size, shape, breakage and crack, porosity, permeability, mineral composition, coal washability, mineral liberation, and exposed grain surface area. 3D imaging systems are ideal techniques to provide the full 3D particle morphology for understanding the behavior of particles in separation processes. Nevertheless, their initial cost is considerable, and proficient technicians are required for operation and maintenance. Despite the ongoing evolution of 3D imaging systems, the simplicity and affordability of 2D image processing methods still make them prevalent for particle measurements. In the future, 3D imaging system will play a key role in the automation and control of mineral processing operations.

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RAZVOJ I PRIMENA 3D SISTEMA ZA SNIMANJE U PRIPREMI MINERALNIH SIROVINA

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Izvod

Trodimenzionalni (3D) sistemi za snimanje površina stekli su popularnost u praćenju statusa i stanja procesa separacije, karakterizacijom unutrašnjih i spoljašnjih struktura čestica kao što su veličina, oblik, gustina i sastav. Ovaj pregledni članak je uglavnom fokusiran na demonstraciju savremenih 3D sistema za snimanje u pripremi mineralnih sirovina, koji su bazirani na nedavnom razvoju 3D senzora. Struktura ovog rukopisa zasnovana je na pregledu dva 3D sistema za snimanje: RhoVol-a i kompjuterske rendgenske tomografije i obuhvata njihove osnovne principe rada. Pored toga, objašnjena je njihova primena u pripremi mineralnih sirovina. U budućnosti, integracijom sa drugim alatima za obradu slike i tehnologijom 3D štampanja, sistem za 3D površinsko snimanje će igrati važnu ulogu u automatizaciji i kontroli procesa prerade minerala.

Ključne reči: *3-D senzori, priprema mineralnih sirovina, RhoVol, kompjuterska rendgenska tomografija, automatizacija.*