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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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AUTOMATIC ASSESSMENT OF CRUSHED ROCK PARTICLE SIZE DISTRIBUTION BASED ON COMPUTER VISION METHODS

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Abstract. Relevance. In the mining industry, control of the particle size distribution of crushed rock material is an important condition for stable operation of crushing and screening plants, mills, screens, and conveyor lines. Traditional sieve analysis provides sufficiently accurate results, but it requires sampling, time, and personnel involvement, and therefore does not always allow rapid response to changes in the technological regime. For this reason, the use of computer vision methods becomes relevant, since they can provide operational assessment of material size from digital images. **Objective.** The objective of this work was to develop and preliminarily test a simple algorithm for automatic assessment of crushed rock particle size distribution using digital images obtained under

laboratory conditions close to conveyor material control. *Methods.* The study used laboratory crushing of rock material in jaw and roll crushers, sieve analysis for fractions above 20 mm, 10–20 mm, 5–10 mm, 2.5–5 mm, 1–2.5 mm, and below 1 mm, digital photographing of samples, and image processing in Python using OpenCV, NumPy, and scikit-image libraries. Particle segmentation was carried out using binarization, morphological filtering, and the watershed algorithm. *Results and conclusions.* It was found that the mean absolute error of automatic assessment was about 4.7 percentage points, while the average correlation coefficient between sieve analysis and computer vision data reached 0.87. The 10–20 mm and 5–10 mm fractions were determined most steadily. The error increased to 7.1 percentage points under one-sided shadow and to 8.3 percentage points with a thick material layer. It is concluded that the proposed approach can be used as an auxiliary tool for operational control at ore mining, coal, cement, and crushed stone enterprises.

Keywords: crushed rock mass, particle size distribution, computer vision, sieve analysis, image processing, crushing and screening plant, digital control, mining industry

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КОМПЬЮТЕРЛІК КӨРУ ӘДІСТЕРІ НЕГІЗІНДЕ ҰСАҚТАЛҒАН ТАУ ЖЫНЫСЫ МАССАСЫНЫҢ ГРАНУЛОМЕТРИЯЛЫҚ ҚҰРАМЫН АВТОМАТТЫ БАҒАЛАУ

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Аннотация. *Өзектілігі.* Тау-кен өнеркәсібінде ұсақталған тау жынысы массасының гранулометриялық құрамын бақылау ұсақтау-сұрыптау кешендерінің, диірмендердің, елеуіштердің және конвейерлік желілердің тұрақты жұмыс істеуі үшін маңызды болып табылады. Дәстүрлі елеуіштік талдау жеткілікті дәл нәтиже береді, бірақ сынама алуды, уақытты және қызметкерлердің қатысуын қажет етеді, сондықтан ол технологиялық режимнің өзгеруіне жедел жауап беруге әрқашан мүмкіндік бермейді. Осыған байланысты материалдың ірілігін кескіндер бойынша жедел бағалауға мүмкіндік беретін компьютерлік көру әдістерін қолдану өзекті болып отыр. *Мақсаты.* Жұмыстың мақсаты конвейердегі материалды бақылауға жақын зертханалық жағдайларда алынған цифрлық кескіндер бойынша ұсақталған тау жынысы массасының гранулометриялық құрамын автоматты бағалаудың қарапайым алгоритмін әзірлеу және алдын ала тексеру болды. *Әдістері.* Жұмыста тау жынысы массасын жақты және білікті ұсатқыштарда зертханалық ұсақтау, 20 мм-ден жоғары, 10–20 мм, 5–10 мм, 2,5–5 мм, 1–2,5 мм және 1 мм-ден төмен фракциялар бойынша елеуіштік талдау, сынамаларды цифрлық фототүсірілімге алу және Python ортасында OpenCV, NumPy және scikit-image кітапханаларын қолдана отырып кескіндерді өңдеу пайдаланылды. Бөлшектерді бөлу үшін бинаризация, морфологиялық сүзгілеу және watershed алгоритмі қолданылды. *Нәтижелері мен қорытынды.* Автоматты бағалаудың орташа абсолюттік қатесі шамамен 4,7 пайыздық пунктті құрады, ал елеуіштік талдау мен компьютерлік көру деректері арасындағы орташа корреляция коэффициенті 0,87 болды. 10–20 мм және 5–10 мм фракциялары ең тұрақты анықталды. Бүйірлік көлеңке кезінде қате 7,1 пайыздық пунктке, ал материал қабаты қалыңдағанда 8,3 пайыздық пунктке дейін өсті. Ұсынылған тәсіл кен өндіру, көмір, цемент және қиыршық тас кәсіпорындарында жедел бақылаудың қосымша құралы ретінде қолданылуы мүмкін деген қорытынды жасалды.

Түйін сөздер: ұсақталған тау жынысы, гранулометриялық құрам, компьютерлік көру, елеуіштік талдау, кескіндерді өңдеу, ұсақтау-сұрыптау кешені, цифрлық бақылау, тау-кен өнеркәсібі

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АВТОМАТИЧЕСКАЯ ОЦЕНКА ГРАНУЛОМЕТРИЧЕСКОГО СОСТАВА ДРОБЛЕННОЙ ГОРНОЙ МАССЫ НА ОСНОВЕ МЕТОДОВ КОМПЬЮТЕРНОГО ЗРЕНИЯ

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Аннотация. *Актуальность.* Контроль гранулометрического состава дробленной горной массы является одним из важных условий эффективной эксплуатации дробильно-сортировочных комплексов, мельниц, грохотов и конвейерных линий в горнодобывающей промышленности. Традиционный ситовой анализ обеспечивает достаточно высокую точность определения гранулометрического состава, однако требует отбора и подготовки проб, значительных временных затрат и участия персонала. Это ограничивает возможности оперативного реагирования на изменения технологических режимов. В связи с этим перспективным направлением является применение методов компьютерного зрения, позволяющих оценивать крупность частиц горной массы на основе анализа цифровых изображений. *Цель.* Разработать и провести предварительную проверку алгоритма автоматизированной оценки гранулометрического состава дробленной горной массы по цифровым изображениям, полученным в лабораторных условиях, имитирующих

контроль материала на конвейерной линии. *Методы.* Экспериментальные исследования включали дробление горной массы на лабораторных щековой и валковой дробилках, ситовой анализ полученного материала, цифровую фотосъемку проб и последующую обработку изображений в программной среде Python с использованием библиотек OpenCV, NumPy и scikit-image. Гранулометрический состав оценивали по следующим классам крупности: более 20 мм, 10–20 мм, 5–10 мм, 2,5–5 мм, 1–2,5 мм и менее 1 мм. Для выделения отдельных частиц на цифровых изображениях применяли методы бинаризации, морфологической фильтрации и алгоритм водораздела (watershed). Результаты автоматизированной оценки сопоставляли с данными традиционного ситового анализа. *Результаты и выводы.* Установлено, что средняя абсолютная ошибка автоматизированной оценки гранулометрического состава составила около 4,7 процентного пункта, а средний коэффициент корреляции между результатами ситового анализа и компьютерного зрения достигал 0,87. Наиболее устойчивые результаты распознавания получены для фракций размером 10–20 и 5–10 мм. При наличии бокового затенения ошибка увеличивалась до 7,1 процентного пункта, а при увеличении толщины слоя материала - до 8,3 процентного пункта. Полученные результаты свидетельствуют о возможности применения методов компьютерного зрения для предварительной автоматизированной оценки гранулометрического состава дробленой горной массы. Предложенный алгоритм может использоваться в качестве вспомогательного инструмента оперативного контроля технологических процессов на горнорудных, угольных, цементных и щебеночных предприятиях. Вместе с тем его практическое внедрение требует дополнительной проверки в производственных условиях с учетом изменяющихся параметров освещения, толщины слоя материала и скорости движения конвейерной ленты.

Ключевые слова: дробленая горная масса, гранулометрический состав, компьютерное зрение, ситовой анализ, обработка изображений, дробильно-сортировочный комплекс, цифровой контроль, горная промышленность.

Introduction. In modern mining operations across many countries, the challenge of improving the efficiency of mineral processing is becoming increasingly significant; this is because extracted ores are often declining in grade, while quality requirements for finished products are rising. Moreover, any crushing and screening of mined material entails substantial energy consumption, equipment wear, and the loss of valuable components if the processing parameters are not optimally selected. One key factor influencing almost all subsequent operations is the particle size distribution of the crushed material. Inadequate control over material size can impair the performance of mills, screens, conveyors, and beneficiation systems, while also increasing the risk of overloads and uneven material feed. Consequently, the ability to rapidly assess particle size is crucial

not only for the crushing stage itself but also for the overall stability of the entire processing chain.

Traditionally, particle size distribution is determined through sieve analysis, involving sampling followed by laboratory measurement. This approach is considered highly reliable, as it relies on the direct separation of material into fractions and yields clear quantitative results. Studies of comminuted products—such as ground dolomite—demonstrate that particle size distribution is a strong indicator of grinding efficiency and process status (Khetagurov et al., 2024). However, this method has obvious drawbacks. It is time-consuming, requires personnel involvement, and necessitates halting or at least interrupting the material flow; furthermore, the resulting data often reflect the process state with a time lag. For modern crushing and screening plants, this is not always practical, as operating conditions may change more rapidly than laboratory analyses can be performed.

Another approach involves the use of indirect process indicators. For instance, particle size can be estimated based on drive power, mill load, vibration levels, conveyor throughput, or the characteristics of the ore itself. Related studies have already demonstrated that digital modeling of the comminution process can aid in understanding material behavior within a ball mill (Chanturia et al., 2025), and that predicting the performance of X-ray fluorescence (XRF) separation can incorporate specific ore fraction characteristics (Tsypin et al., 2024). A key advantage of these methods is their ability to operate without direct visual contact with the material, often utilizing existing data from automated control systems. However, a drawback is that the relationship between the signal and actual particle size is not always straightforward; it is influenced by factors such as moisture content, fragment shape, density, mineralogical composition, and the technical condition of the equipment.

In recent years, increasing attention has been paid to machine learning and image analysis methods, as they enable a shift from periodic monitoring to the near-continuous assessment of flow parameters. The mining industry is actively exploring techniques for object recognition, geological data classification, and image analysis. For instance, neural network approaches are being applied to map fracture patterns on open-pit mine walls (Skorobogatko et al., 2024), identify gold-bearing mineralization via satellite imagery (Davydenko et al., 2025), and segment natural features during drone-based monitoring of mining areas (Mikhailov et al., 2025). These examples demonstrate that computer vision is no longer a novel field in geology and mining, although its implementation in specific operational settings often encounters practical challenges.

Computer vision can be particularly valuable for assessing particle size distribution, given that crushed rock mass is inherently a visually observable object. A camera installed above the conveyor or near the discharge zone can capture images of the material flow; an algorithm then identifies the outlines of the fragments, estimates their sizes, and generates an approximate size distribution.

While this method does not entirely replace sieve analysis, it provides a real-time overview of changes in particle size. This is particularly valuable when it is necessary to quickly determine whether crusher performance has shifted—for instance, if there is an increased yield of oversized material or, conversely, if over-crushing is occurring. A similar approach can be applied to identifying ore content on the conveyor using clustering methods, which also involves the automatic extraction of material characteristics from the flow (Osipova et al., 2024).

However, the computer vision method has its limitations. Accuracy is affected by lighting, dust, surface moisture, particle overlap, irregular particle shapes, and image scale. Furthermore, the camera captures only the top layer of the material rather than the entire volume of the flow. Consequently, the resulting estimate is always somewhat approximate and should be viewed as a real-time operational metric rather than a high-precision laboratory analysis. Yet, this is precisely the practical value of this study: there is no need to immediately build a complex, universal system; it suffices to verify the feasibility of automated particle size assessment under specific conditions and compare the results against reference data. This approach aligns better with actual production environments, where the requirement is often not for an ideal model, but for a simple, functional solution.

The relevance of this research direction is also linked to the broader digitalization of the mining industry. Systems for equipment monitoring, failure prediction, and process parameter control are currently of great importance. Vibration analysis is already employed for diagnosing diesel engines and power equipment (Afanaseva et al., 2025), and condition assessment of complex machinery—such as centrifugal compressors—is becoming part of the general shift toward intelligent control (Afanaseva et al., 2026). In the mining industry, equipment reliability and process controllability are regarded as key factors in operational efficiency (Malozyomov et al., 2024; Shishkin et al., 2024). If a machine vision system enables the early detection of deviations in material size, it could indirectly reduce overloads, emergency shutdowns, and excessive energy consumption.

Machine learning methods are already being applied to geophysical data interpretation—for instance, in the automated classification of magnetic anomalies in the North Caucasus (Tynchenko et al., 2026) and the identification of seismic facies features using self-organizing neural networks (Malikov et al., 2026). These studies demonstrate that even complex natural objects can be formalized using digital features, provided the initial data and processing algorithms are selected correctly. For crushed rock mass, the situation is simpler in one sense—as the object is directly observable—but more complex in another, given that the image contains a multitude of irregular shapes, shadows, and overlapping elements.

Furthermore, the issue of granulometry is significant not only for ore beneficiation but also for the processing of industrial by-products and construction materials. Finely dispersed powders, rock wool waste, ash-and-slag materials, and basalt additives are utilized in construction systems where particle size profoundly

influences material properties (Klyuev et al., 2025; Klyuev et al., 2024; Nurgaliyeva et al., 2026; Petropavlovskaya et al., 2025). Consequently, the development of automated methods for assessing particle size may find applications extending well beyond mere crusher monitoring at mining operations. Research into powder materials and their activation in ball mills also indicates that changes in particle size and state constitute a critical technological factor determining the material's subsequent properties (Martyushev et al., 2014). Digital parameter assessment methods are becoming increasingly important even in the analysis of crystalline structures and materials science specimens, as evidenced by the comprehensive X-ray diffraction analysis of silicon carbide (Bosikov et al., 2023).

Thus, the application of computer vision to assess the particle size distribution of crushed rock mass represents a relevant area of study, bridging a practical industrial need with modern digital data processing techniques. Such a system can serve as a valuable tool for process engineers, enabling them to rapidly detect changes in material size and make informed decisions regarding the adjustment of crushing and screening complexes. The aim of this work is to develop and preliminarily test a compact computer vision algorithm for the automated assessment of the particle size distribution of crushed rock mass, using images of the material obtained under conditions simulating industrial conveyor operations.

Materials and Methods. The experimental plan was designed to test not the entire potential automated monitoring system, but rather a single, crucial element: the feasibility of assessing the particle size distribution of crushed rock mass using digital images. The first stage involved preparing a batch of crushed material and obtaining reference data via sieve analysis; subsequently, the same samples were photographed and the images processed. The results obtained through computer vision were then compared with those from manual size-fraction separation. This approach was chosen because, for industrial application, it is essential to understand not only how the algorithm functions but also how its readings correlate with the standard monitoring methods already employed at production facilities.

The material studied consisted of crushed rock mass produced by laboratory-scale crushing of a medium-strength parent rock. No special effort was made to achieve an idealized material state, as industrial conditions involve fragments with irregular shapes, rough surfaces, and chipped edges, as well as instances of partial overlap. This distinction is important because a laboratory sample that is too "clean" might yield impressive results, yet the resulting algorithm could perform poorly on an actual conveyor line. Material preparation was carried out using a laboratory jaw crusher (such as the ShDS type or a similar unit commonly found in mining-related educational and research laboratories). The maximum feed size was 40 mm, and the discharge gap was set between 5 and 10 mm. To achieve a more diverse particle size distribution, a portion of the material was additionally processed through a roll crusher with a gap setting of approximately 3–5 mm.

Following crushing, the material was thoroughly mixed, and samples

weighing approximately 1.5–2.0 kg were obtained using the quartering method. The reference particle size distribution was determined using a standard set of laboratory sieves with aperture sizes of 20, 10, 5, 2.5, and 1 mm. Sieving was performed using a vibrating screen or a laboratory sieve analyzer for 5 minutes at a medium oscillation amplitude. After sieving, each fraction was weighed on an electronic scale with an accuracy of 0.1 g. The resulting values served as baseline data for comparison, although it is understood that sieve analysis itself is subject to error due to grain shape and the incomplete passage of particles through the mesh openings.

To capture images, a simple setup was assembled that could be replicated in a standard university laboratory. A digital camera with a resolution of 12–16 MP was used, mounted on a tripod 60–70 cm above the working surface. A dark matte sheet served as the working surface to ensure that light-colored and gray rock fragments stood out clearly against the background. Lighting was provided by two 20–30 W LED lamps positioned at an angle to the surface to minimize harsh shadows. Before imaging, a 100 mm scale bar was placed next to the material to calibrate the pixel size. While simple, this approach is industrially significant, as the underlying principle could later be adapted for a conveyor line, replacing the laboratory table with a moving belt.

Images were captured in triplicate for each prepared sample. The material was spread in a thin layer—without heavy compaction, yet without manually separating every individual particle. This was done intentionally, as it is impossible to completely eliminate particle overlap in actual industrial production. Between 8 and 12 images were obtained for each sample; some were used to configure the algorithm, while others were reserved for validation. Images were saved in JPEG format, maintaining a constant focal length and a fixed distance between the camera and the surface. Prior to processing, the region of interest was cropped, brightness was normalized, and the image was converted to a color space suitable for separating the material from the background.

Image processing was performed in a Python environment using the OpenCV, NumPy, and scikit-image libraries. First, the image was converted to grayscale, followed by median smoothing to reduce fine noise. Subsequently, threshold-based binarization and morphological processing were carried out; the latter included removing small objects and filling minor gaps in the contours. A watershed algorithm based on a distance map was used to separate touching fragments. For each identified object, the area, equivalent diameter, maximum length, and minimum width were determined. For comparison with sieve analysis, the particle's equivalent diameter—converted from pixels to millimeters using a scale bar—was adopted as the primary metric.

To evaluate the results, all identified particles were categorized into the same size fractions used in the sieve analysis. The mass fraction of each category was then calculated; however, since image analysis primarily yields particle area, a

simplified conversion method was adopted based on the assumptions of uniform material density and mass proportionality to particle volume. Particle shape was accounted for approximately via a shape factor, which was kept constant across the entire series of experiments. While this approach is not perfectly precise, it allows for the validation of automated monitoring feasibility within the scope of a specific applied task. From an industrial perspective, even such an estimate is valuable, as it provides a rapid indication of shifts in material size distribution without the need to wait for laboratory analysis.

The method's accuracy was assessed by comparing the fractions obtained via image analysis with those from sieve analysis. Additionally, the mean absolute error across fractions was calculated to identify which size classes were less accurately recognized. Particular attention was paid to large fragments, as these most frequently cause issues during downstream crushing, screening, and mill feeding. Therefore, the industrial significance of the work lies not only in improving measurement accuracy but also in the ability to timely detect disruptions in the crushing process, which subsequently lead to excessive energy consumption, reduced productivity, and increased equipment wear.

Results and Discussion. The work yielded experimental data demonstrating that using computer vision to assess the particle size distribution of crushed rock mass can produce reasonably acceptable results, even with a relatively simple laboratory setup. A total of 12 samples of crushed material, weighing between 1.48 and 2.05 kg, were prepared. Each sample underwent sieve analysis followed by photography against a dark background and subsequent image processing. A total of 126 images were used: 84 for calibrating processing parameters and 42 for validating the resulting algorithm. While this dataset is not extensive, it is sufficient for a preliminary assessment of the method's feasibility, given that the study focused on a specific, small-scale applied task rather than the development of a full-scale industrial system.

Sieve analysis revealed that the material under study exhibited a broad particle size distribution. The average content of the >20 mm fraction was 6.8%; the 10–20 mm fraction, 18.4%; the 5–10 mm fraction, 31.7%; the 2.5–5 mm fraction, 26.1%; the 1–2.5 mm fraction, 12.9%; and the <1 mm fraction, approximately 4.1%. This distribution is typical for material processed via jaw crushing followed by partial secondary crushing in a roll crusher. Notably, the content of the 5–10 mm fraction varied between 27.4% and 36.9% across individual samples, demonstrating material heterogeneity even under laboratory conditions. This is significant for the mining industry, as fluctuations in particle size can be even more pronounced in actual crushing and screening plants, and operators may not always detect changes in the material until obvious issues arise at the screen or mill. During image processing, the algorithm reliably identified large and medium-sized particles. The 10–20 mm and 5–10 mm fractions were recognized with the highest confidence, as they exhibited distinct contours and contrasted well against the background. The mean

error in determining the proportion of the 10–20 mm fraction was 3.1 percentage points, while for the 5–10 mm fraction, it was 3.8 percentage points. The error was higher for the 2.5–5 mm fraction, averaging 5.2 percentage points. This is attributed to the fact that smaller particles were frequently situated between larger pieces, partially fell into shadow, and were sometimes merged into a single object by the algorithm. Accuracy was lowest when assessing the fraction smaller than 1 mm, with a mean discrepancy of 6.4 percentage points compared to sieve analysis. Consequently, the proposed approach is better suited for the rapid monitoring of primary and coarse fractions rather than for the precise quantification of the dust-like component of the material.

A comparison of the automated assessment results with sieve analysis revealed a total mean absolute error of 4.7 percentage points across all fractions. The correlation coefficient between the fraction proportions obtained via the two methods ranged from 0.82 to 0.91 across different samples, with a mean value of 0.87 (Fig. 1). This indicates that the method generally captures changes in particle size distribution accurately, even though individual values do not always align perfectly. Notably, whenever the content of coarse material (larger than 10 mm) increased, the algorithm detected this change in almost every instance. For example, in sample No. 4, sieve analysis showed a combined content of fractions larger than 10 mm of 29.6%, whereas computer vision data indicated 31.2%. In sample No. 9, these values were 21.8% and 23.5%, respectively. Such a discrepancy is not critical for real-time industrial monitoring, because for a process engineer, seeing the direction of change is often more important than achieving laboratory-grade accuracy at every moment.

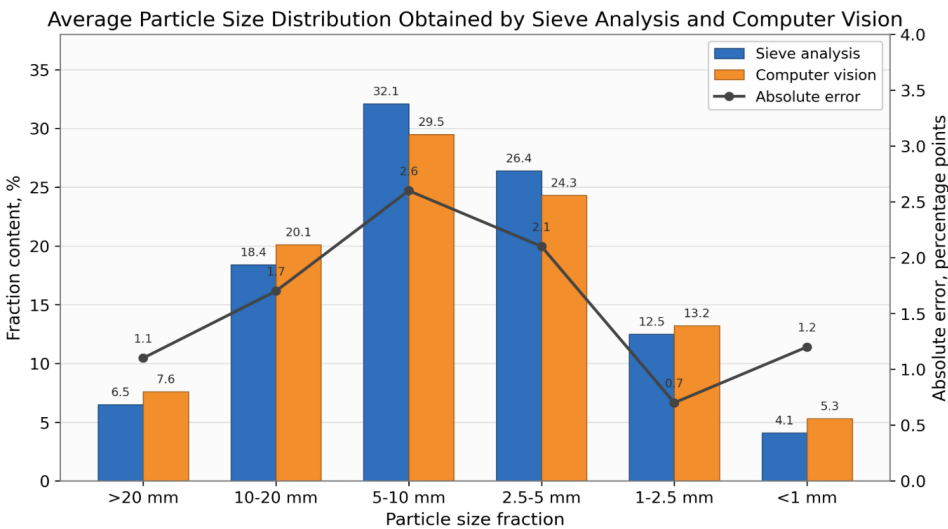


Figure 1. Average particle size distribution of crushed rock material determined by sieve analysis and computer vision, with absolute error for each size fraction.

Table 1. Comparison of Sieve Analysis and Computer Vision Results for Crushed Rock Size Distribution.

Sam- ple No.	Sam- ple mass, kg	>20 mm by sie- ve, %	>20 mm by CV, %	10– 20 mm by sie- ve, %	10– 20 mm by CV, %	5–10 mm by sie- ve, %	5– 10 mm by CV, %	2.5– 5 mm by sie- ve, %	2.5– 5 mm by CV, %	1– 2.5 mm by sie- ve, %	1– 2.5 mm by CV, %	<1 mm by sie- ve, %	<1 mm by CV, %	Mean absolute error, p-p.
1	1.48	5.9	6.7	17.6	19.1	32.4	30.8	26.8	24.9	13.1	12.0	4.2	6.5	1.5
2	1.55	7.2	8.4	18.9	20.7	30.6	28.9	27.5	25.1	11.8	12.6	4.0	4.3	1.4
3	1.62	6.5	7.1	19.4	21.2	31.9	29.5	25.7	24.1	12.5	13.2	4.0	4.9	1.3
4	1.73	8.1	9.5	21.5	21.7	29.3	27.0	25.8	24.6	11.4	12.3	3.9	4.9	1.2
5	1.69	4.8	5.9	16.7	18.5	36.9	33.4	24.2	22.7	12.8	13.9	4.6	5.6	1.7
6	1.81	6.9	8.2	17.9	20.1	33.5	30.2	25.1	23.0	12.6	13.3	4.0	5.2	1.8
7	1.88	7.5	8.7	18.2	20.4	30.8	28.1	27.9	25.2	11.9	12.8	3.7	4.8	1.8
8	1.94	5.6	6.2	17.4	19.8	34.2	31.0	25.6	23.3	13.0	13.7	4.2	6.0	1.8
9	2.05	4.9	5.7	16.9	17.8	35.6	32.9	26.4	23.8	12.1	13.5	4.1	6.3	1.7
10	1.97	7.8	9.3	19.1	21.6	27.4	25.0	28.6	25.9	13.2	13.8	3.9	4.4	1.7
11	1.76	6.1	7.4	18.6	20.2	31.2	28.5	26.7	24.2	13.0	13.9	4.4	5.8	1.7
12	1.84	7.0	8.1	18.5	20.6	31.0	28.6	26.9	24.4	12.4	13.1	4.2	5.2	1.7
Ave- rage	1.78	6.5	7.6	18.4	20.1	32.1	29.5	26.4	24.3	12.5	13.2	4.1	5.3	1.6

As can be seen from Table 1, the computer vision method slightly overestimated the coarse fractions and underestimated the 5–10 and 2.5–5 mm fractions in most samples. This is mainly connected with the overlapping of particles and the conversion of visible particle area into an equivalent particle size. However, the general trend of the size distribution was reproduced correctly, which is important for operational control of crushing and screening equipment.

The algorithm's performance under varying lighting conditions was also evaluated separately. With uniform illumination provided by two LED lamps, the average error was 4.3 percentage points. When one lamp was turned off, resulting in more pronounced shadowing, the error increased to 7.1 percentage points (Fig. 2). This demonstrates that imaging conditions are a key factor influencing the results. In industrial settings—such as coal mining or non-ferrous metal ore processing—factors like dust, vibration, and uneven lighting can have an even greater impact on image quality. Therefore, adapting the method for an industrial conveyor line requires incorporating a camera enclosure, stable lighting, and a system for regularly cleaning the protective glass. Without these measures, even a robust algorithm may yield inconsistent data.

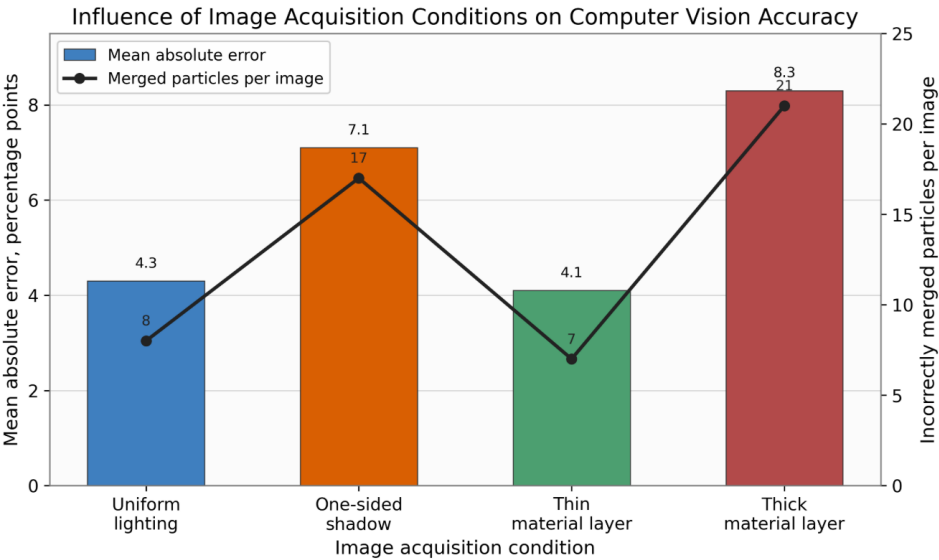


Figure 2. Influence of image acquisition conditions and material layer thickness on the accuracy of computer vision-based particle size assessment.

It was also determined that accuracy depends on the thickness of the material layer. When the sample was spread relatively evenly and particles barely overlapped, the error in determining the size distribution did not exceed 3.9–4.5 percentage points. As the layer thickness increased and significant overlapping occurred, the error rose to 8.0–8.6 percentage points. This represents a significant limitation, given that material on an actual conveyor belt often moves as an uneven stream rather than a single layer. However, the computer vision system can still be useful if viewed as an indicator of changes in particle size rather than a complete replacement for sieve analysis. For the cement industry, non-metallic construction materials sectors, and crushed stone plants, such information can help rapidly adjust crushing parameters and reduce the yield of oversized material.

Analysis of individual images revealed that the algorithm sometimes erroneously merged two closely spaced particles into a single large one. This occurred most frequently with dark grains exhibiting low boundary contrast. The watershed algorithm partially mitigated this issue but did not resolve it entirely. After fine-tuning morphological processing parameters, the frequency of such errors dropped from approximately 18–20 to 7–9 instances per image for samples of average coarseness. However, particle separation remained less robust in the presence of a high proportion of fine fractions. While more sophisticated neural network-based segmentation methods could be employed in the future, the classical algorithm was deliberately retained for this study because it is simpler, more cost-effective, and can be implemented without high-performance computing hardware.

From an industrial perspective, a key finding is that the processing time per

image averaged 0.8–1.4 seconds on a standard computer equipped with an Intel Core i5 processor and 16 GB of RAM. Even accounting for image acquisition and pre-filtering, this enables particle size assessment at intervals of 5–10 seconds. For a crushing and screening complex, this speed is quite sufficient, as adjusting the operating mode of a crusher or screen does not typically require a sub-second response. In the mining industry, such monitoring can be used to prevent oversized material from entering the mill, while in the coal industry, it helps control the quality of prepared fuel prior to stockpiling or shipment. Furthermore, this approach is valuable for crushed stone producers, where particle size distribution is directly linked to product grade and market value.

The results demonstrate that automatic size assessment should not be viewed in isolation from the overall technological process. If the system detects an increase in the fraction exceeding 20 mm, this may indicate wear on the crusher's working parts, a change in the raw rock's strength, or irregularities in the feed rate. Conversely, an increase in the fine fraction (under 2.5 mm) may point to over-crushing, excessive crushing force, or material recirculating through the crusher. Both scenarios are industrially significant: oversized material reduces the efficiency of downstream grinding, whereas an excess of fines can impair screening performance, increase dust levels, and lead to material loss.

Overall, the study confirmed that even a simple computer vision system—based on a standard digital camera, controlled lighting, and OpenCV algorithms—can determine the particle size distribution of crushed rock with accuracy sufficient for real-time monitoring. While the method does not replace laboratory sieve analysis (particularly for fine fractions), it serves as a valuable complement due to its high speed and capacity for repeated measurements. The most promising practical application involves installing such systems on conveyors downstream of the crushing stage at mining, coal, cement, and crushed-stone operations. For these facilities, it is crucial not only to know the precise composition of a sample after analysis but also to detect changes in material quality within the flow in a timely manner, as these changes directly impact productivity, energy consumption, and equipment wear.

Conclusion. The study demonstrated that using computer vision to automatically assess the particle size distribution of crushed rock mass serves as a simple yet highly useful tool for real-time monitoring. The objective was not to completely replace traditional sieve analysis, as the latter remains the more accurate method for laboratory assessment. However, the results indicate that digital image processing enables the rapid determination of the material's overall distribution across key size fractions and the timely detection of changes in the flow's coarseness.

Experimental results showed that the mean absolute error of the automated assessment was approximately 4.7 percentage points, while the correlation coefficient between sieve analysis data and computer vision data averaged 0.87.

The 10–20 mm and 5–10 mm fractions were identified most reliably, whereas the error was higher for fine particles (under 1 mm) due to shadows, particle overlap, and poor edge definition. It was also found that lighting quality and material layer thickness significantly affect the results: the error rose to 7.1 percentage points with the appearance of side shadows and to 8.3 percentage points with a thicker material layer.

The practical significance of this work lies in the potential application of the proposed approach at crushing and screening facilities within the mining, coal, cement, and crushed stone industries. Such a system enables faster detection of oversized material, over-crushing, and deviations from optimal crushing parameters. Future work should focus on testing the methodology on a moving conveyor belt and incorporating neural network-based segmentation algorithms.

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