International Journal of Rock Mechanics & Mining Sciences 82 (2016) 48–60

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Block delineation algorithm for rock fragmentation analysis

Jeong-Hun Han, Jae-Joon Song *

Department of Energy Systems Engineering, Seoul National University, 599 Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea

ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form
18 November 2015
Accepted 22 December 2015
Available online 31 December 2015

Keywords:
Block delineation algorithm
Stereophotogrammetry
Three-dimensional point-cloud
Surface-based estimation

ABSTRACT

A block delineation algorithm that distinguishes individual blocks from a muckpile is developed. Blocks are modeled in three dimensions using stereophotogrammetry, and its three-dimensional point-cloud is used as the input data for the block delineation algorithm. This algorithm delineates each block based on the geometrical features of blocks within a scattered or heaped muckpile. The applicability of the algorithm is investigated through laboratory and field experiments. The fragmentation of scattered blocks can be obtained by the proposed delineation algorithm. For analyzing the fragmentation of heaped blocks, the block delineation algorithm is integrated into the statistical estimation method that was developed in a previous study of Han and Song, which is referred to as the surface-based estimation. The algorithm developed in this study was first used to delineate and analyze the blocks, and the fragmentation was subsequently estimated using the surface-based estimation.

1. Introduction

The efficiency and productivity of blasts are estimated through fragmentation analysis, and the fragmentation is generally expressed in the form of the size distribution. The results from fragmentation analysis can be used in the estimation for the attainment of blast design and can contribute to the optimal blast by using them as feedback data for the design of the subsequent blast. If blast causes large rocks especially in quarry blast, it is important to estimate the accurate size distribution of the entire muckpile because the size of large blocks is the essential factor for the design of loading and transportation system.

The quantitative estimation for fragmentation can be accomplished most accurately through the sieve test. The sieve test, however, is available for small-sized materials and is not suitable for large-sized materials, such as rocks. In rock mechanics, the quantitative estimation for fragmentation is generally performed with indirect methods, such as photogrammetry. The basic principle of this indirect method is to analyze the sizes of rocks by comparing rocks in the image with the scale bar in the same image.[1] With the advance of image processing technology and the demand of automatic processing for fragmentation analysis, the related technologies based on 2D image processing have been developed. Split Desktop, WipFrag and FragScan are the most popular software packages based on 2D image processing that analyze the image using the information of brightness. In general, the area and boundary information of an object in the image can be analyzed automatically with these software packages used in research.[2–8] The 3D analysis using the information obtained from 2D image processing has been performed in research[9,10] to overcome the restriction of 2D image processing. In this method, the shape of a rock is assumed to be a perfect circle in 2D analysis and a perfect sphere in 3D analysis. First, the equivalent diameter is calculated from the information of area based on the assumption that the shape is a perfect circle. Then, the volume is calculated using this equivalent diameter based on the assumption that the shape is a perfect sphere. The size distribution is analyzed using the information of this equivalent diameter and volume. However, more geometrical features such as a 3D point-cloud are not utilized in this method, while such information can be obtained using stereophotogrammetry. As the computer technologies have advanced, research has focused on the restoration of an object in the image in 3D space. Fragmentation analysis based on this 3D method has been performed in research. Noy[11] analyzed the size distribution of the muckpile on a conveyor belt using stereophotogrammetry, and Muller[12] analyzed the volume of the blasted muckpile using a laser scanner. Thurley[13] obtained the 3D information of the muckpile using a laser scanner and analyzed the size distribution using the watershed method. Han and Song[14] performed the fragmentation analysis based on the statistical estimation. First, 3D information such as a 3D point-cloud was obtained using stereophotogrammetry. Then, each surface block was analyzed individually from the entire muckpile. Finally, the size distribution of the entire muckpile was analyzed using the information of surface blocks as the input parameter for the

* Corresponding author.
E-mail address: songjj@snu.ac.kr (J.-J. Song).

http://dx.doi.org/10.1016/j.ijrmms.2015.12.005
1365-1609/

statistical estimation. Each surface block needed to be modeled and analyzed manually, not automatically, in the study of Han and Song,[14] even though that method yielded more accurate results than 2D image processing. In the field of computer vision, there has been a great deal of research on reconstructing object surfaces,[15–17] and point-cloud has been a good research reference source. Such research has contributed to the development of 3D modeling, such as in meshing, triangulation and rendering. Additionally, many researchers have focused on extracting the features of an object and recognizing shapes. Bryant et al.[18] identified shapes using 2D binary image; shapes were identified based on the boundary. Chuang et al.[19] recognized shapes using vertices and edges. Vertices were classified into several groups in accordance with a priori knowledge, and shapes were recognized by connecting vertices and edges. Du et al.[20] extracted features from an object using various color spaces and compared the performances of the various classification methods. Baykan et al.[21] identified rocks using color features. Thin sections of the samples were acquired and investigated with a microscope, and the minerals in rocks were classified based on their color features. Ishikawa et al.[22] developed a classifier based on Raman spectra, and analyzed igneous rocks.

This study aims to develop a new algorithm for fragmentation analysis. Rocks collected for this study were investigated to find similarities between various rock samples. The developed algorithm used the 3D point-cloud as input data, while its color information was not used because the color information did not provide a large effect on detecting the boundary between rock blocks. The block delineation algorithm was developed to distinguish each surface block from the entire muckpile and was then integrated into the method of Han and Song.[14] The applicability of this combined algorithm was estimated through laboratory and field experiments.

2. Background theory

2.1. Stereophotogrammetry

Stereophotogrammetry is a method that extracts the 3D information of an object using a stereo-image. A stereo-image is composed of images taken from various directions, such as left and right images. The basic principle of stereophotogrammetry is to find the matching points between images. For example, the left image is set as the reference image, and the right image is set as the correlated image. Next, correlations between the first point in the reference image and all of the points in the correlated image are estimated. Then, the point in the correlated image that has the highest correlation with the first point in the reference image is classified as the corresponding point. In this method, every matching point between images is explored. However, it takes a large amount of the time to calculate the correlation between points. Therefore, the corresponding point in the correlated image is explored within a search window that has a certain size. In general, images taken from random directions are preprocessed such that the photographing directions are parallel to each other using a rotation matrix along the x-, y-, and z-directions, which is responsible for the minimization of the calculation time. It is, therefore, beneficial to obtain images simultaneously with a stereo camera that has a stereo lens and parallel photographing directions.

2.2. Pattern recognition

Pattern recognition is a technique that is used to classify data of interest based on a specific feature. This specific feature is defined in advance by analyzing the similarity between data. The design of a pattern recognition system is mainly composed of the following five steps.[23] In the data collection step, it is important to collect a large amount of data to assure good system performance. It is highly improbable to find the feature that can perfectly represent the entire system; therefore, it is critical to collect as much data as possible, except for the case where a certain feature is prominent. The feature selection is the most important step for the design of the pattern recognition system. Therefore, proper prior knowledge should be obtained by analyzing the data of interest. It is important to select the simple feature and the strong and rigid feature against noise. In the model selection step, it is impossible to evaluate the system performance without the actual information of the data. Therefore, it is necessary to select a proper model by analyzing the data of interest. In the training step, the most effective feature, the *classifier*, is determined and/or developed after sufficient analysis of the data of interest. Finally, in the evaluation step, the performance of the developed system is evaluated. The system can then be improved, if necessary.

2.3. Surface-based estimation

The statistical approach for estimating the size distribution for a muckpile was suggested in the previous study of Han and Song.[14] In a muckpile, the information of surface blocks can be obtained intuitively and easily. Han and Song, therefore, estimated the size distribution for a muckpile based on the surface blocks of the muckpile. First, the entire muckpile was modeled in three dimensions, and its volumetric information was obtained. Next, each surface block was modeled in the same method, and its volumetric information was obtained. Then, a sphere with the same volume as each surface block was considered, assuming that every rock block is a perfect sphere. Based on this assumption, the size information of each surface block was calculated using the volume formula of a sphere. After a frequency count analysis of the diameter of the surface blocks, a probability density function (PDF) was determined to fit the size distribution of the surface blocks. Then, the cumulative distribution function (CDF), which has a horizontal axis of diameter and a vertical axis of probability, was determined. Finally, the probability was generated randomly, and its corresponding diameter was calculated using the inverse function of the CDF.

3. Block delineation algorithm

In 2D image processing technology such as Split Desktop, blocks are delineated and analyzed automatically. The results from 2D image processing technology, however, are less accurate than those from stereophotogrammetry and statistical estimation.[14] In addition, care should be taken in the step of manual editing because several small blocks are likely to merge into one large block or one large block becomes divided into several small blocks in the step of auto-delineation. Meanwhile, in the analysis of Han and Song,[14] the surface blocks needed to be analyzed individually from the muckpile, even though this method provided more accurate results than 2D image processing.

This study aims to develop an algorithm that distinguishes each block of the muckpile based on stereophotogrammetry. The algorithm developed in this study, the block delineation algorithm, uses the 3D point-cloud of the entire muckpile and delineates each block based on the features that the block shapes have in common. The basic assumption applied to this algorithm is that the shape of a rock is convex, and the overall procedure is as follows. First, the algorithm detects peaks that are defined in this study and delineates the top block with the top reference peak that has the