Fracturing Proppant Quality Estimation Based on Fuzzy Connectedness and Shape Similarity

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ABSTRACT To improve the accuracy and efficiency of measuring fracturing proppant sphericity and roundness, a measurement scheme is designed by combining fuzzy connectedness and shape similarity. Firstly, in the proppant images collected by the microscope, according to the color characteristics of the test placement plane’s hole and proppant, the region of each proppant and that of the hole without proppant are marked separately. Secondly, based on the feature of holes without proppant, the statistical method of labeling connected components is used to only reserve all the proppant regions. Thirdly, select a part of the region of each proppant as the seed region to calculate the fuzzy connectedness map between seed regions and other regions. Fourthly, select the appropriate connectedness threshold for each proppant based on histogram of fuzzy connectedness map of each proppant region to obtain the accurate region of each proppant. Finally, the shape similarity measurement method based on Hu moment is used to determine the sphericity and roundness of each proppant by measuring the similarity between the region of each proppant and that of 20 particles in the standard template. The experimental results show that the proposed scheme is consistent with manual measurement flow, and can avoid the human labor, meanwhile, the accuracy of measurement is basically consistent with the results of manual measurement.

INDEX TERMS Proppant, fuzzy connectedness, Hu moment, sphericity, roundness.

I. INTRODUCTION Fracturing proppant is a kind of granular product and mostly sintered from ceramic materials. Fracturing proppant has high fracturing strength and is widely used in deep well and high-pressure oil and gas reservoir fracturing. During deep oil and gas production, the high-close-pressure low-permeability ore deposits are fractured and the oil-bearing rock layers are fractured. Then, oil and gas are collected from the channels formed by fractures. Fracturing proppant is used to enter the formation with a high-pressure solution to fill the cracks in the rock formation. The fracturing proppant supports the cracks without closing by stress release and plays an important role in increasing production by maintaining high conductivity and allowing oil and gas to flow smoothly. It has been proved that the oil well with fracturing proppant increases the production by 30-50% and extends the service life of oil and gas wells [1].

To ensure the quality of fracturing proppant used in oil and gas field development, it is necessary to measure the sphericity and roundness of fracturing proppant before actual use. At present, some different standards for fracturing proppants performance tests are set up in different countries, such as the American high-strength proppant test method API RP60, the international standard ISO 13503-2 fracturing proppant evaluation method, the Chinese industry standard SY/T5108-2006 “Specification and recommended testing practice for proppants used in hydraulic fracturing operations” and the petroleum and natural gas industry standard of the people’s Republic of China Q/SY125-2007 “Standard for evaluating the performance of fracturing proppant” [2]. According to [2], the determination of sphericity and roundness of fracturing proppant is tested with a visual roundness and sphericity template shown in FIGURE 1, in which the green numbers of particles we marked will be used in the subsequent comparative experiments. The standard template of FIGURE 1 is proposed by Wadell [3] and Krumbein [4], and it is one of the most widely employed methods. The specific test

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process is based on two steps. Firstly, 20-30 proppant samples are taken out of the tested proppant samples randomly. Then, the selected samples are put under the solid microscope for observation. The obtained micrograph is used to determine the sphericity and roundness of each proppant according to the standard template, and the average sphericity and roundness of this batch of proppant samples are calculated. The standard does not specify which method is used to determine the sphericity and roundness of each proppant by micrograph. Generally, manual measurement method is used, but there are some problems such as poor repeatability and low efficiency of the measurement process, because the procedure depends on personal observation.

To improve the efficiency and accuracy of the measurement procedure for particle roundness and sphericity, many scholars in the world have designed a series of evaluation methods. Generally speaking, there are two methods of particle shape measurement: fractal geometry based on image and parameters based on image. Fractal geometry has been utilized in numerous fields, such as biology, geography, meteorology and material science, especially in civil engineering. There are a lot of studies that have been applied to determine the fractal dimensions of particles. To reveal the engineering properties of soil, some researchers [5]–[7] have devoted to the study about the effect of fractal dimension of particles. Arasan et al. [8] has used the concept of fractal dimension to describe the shape of particles, and he has found the exponential relationships between the fractal dimension and roundness, sphericity, angularity, convexity. Pan et al. [9] has proposed an algorithm for determining roundness and sphericity of fracturing proppant based on fractal theory and shape context method. In the algorithm, the radius-angle distribution of each proppant edge has been used to determine the sphericity, and the fractal dimension has been used to determine the roundness.

In the research field of parameters based on image, some scholars have found that the computer-aided method could not only bring the industry new practical methods to determine the particle size with good results [10], but also bring great help to reduce the measuring time dramatically [11], [12]. Zhang [13] has deduced the algorithm of sphericity and roundness of fracturing proppant by solving the area and perimeter of the particle projection image to reveal their characteristics. However, it was found by experiments that the sphericity and roundness of his method were different from those of standard templates. Rodriguez et al. [14], [15] has made a great contribution to particle shape parameters evaluation. He has introduced a 2-D image analysis method to classify particle shape for coarse-grained materials, and he has reviewed soil classification methods for particle shape and geometrical shape descriptors. Then, he has summarized the description of particle shape and quantitative measurement methods, and he has given the calculation formulas of roundness and sphericity of particles. Pei et al. [16] has utilized computer image processing technology to determine the proppants’ roundness and sphericity based on the parameters of each proppant including area, perimeter, maximum inscribed circle and minimum circumscribed circle, and the curvature of corner points. Takashimizu and Liyoshi [17] has used the aspect ratio of particles to add new parameters for the measurement of roundness of particles, but he has not elaborated on the measurement of sphericity. Based on tests of digital circle and ellipse images using ImageJ software, he has revealed the relationship between roundness and the aspect ratio using a parameter function. Wang et al. [18] has used corner detection and calculated the radius of maximum inscribed circles to evaluate the roundness of limestone particles. Zhang et al. [19] has evaluated the shape of breakstones using the original method proposed by Wadell [3] and Krumbein [4]. Fang et al. [20] has used Fourier transform to calculate the roundness and sphericity in terms of describing the particle shape of sandy soil. Zheng and Hryciw [21], [22] and Hryciw [23] have used computational geometry methods to determine the roundness and sphericity for soil through threshold segmentation. They have used Adobe Photoshop lasso tools to delineate particles with full projections from images of three-dimensional particle assemblies. In recent years, the author has been persisting in the research on the measurement method of sphericity and roundness for fracturing proppants. Some methods of using image processing technologies have been proposed to determine the quality of proppants [16], [24]. In both methods, the edge detection and corner detection algorithms have been used in the proppant processing. The parameters of maximum inscribed circle and the minimum circumscribed circle of each proppant have been used to determine its sphericity by a fitting formula, and the curvature of each corner in the edge of particles has been also used to figure out the roundness of particles in a function. Both methods have been taken in the Changqing oilfield technical monitoring center for practical application.

All methods above are inevitably related to extracting each particle from the micrograph of proppant, and the threshold method are used in most of them, which could not achieve satisfactory particle extraction results for all micrographs of

FIGURE 1. Standard template of sphericity and roundness.
different kinds of proppants. At present, although the manual measurement method has some shortcomings, its accuracy is the highest level. The process of manual measurement method is firstly extracting each proppant, and then comparing the shape of proppant with 20 particles in the standard template by human beings. So, the proppant extraction is the key to determine proppant’s sphericity and roundness accurately. To be consistent with the process of the manual measurement method, an effective and automatic proppant extraction method should be selected under comprehensive consideration. Based on the principle of avoiding human interaction and relatively high accuracy of target extraction, a proppant extraction method based on fuzzy connectedness algorithm [25]–[27] is introduced to extract each proppant from the micrograph to achieve a higher accuracy of proppant extraction without human interaction. Then, for the determination of sphericity and roundness, instead of calculating through some relevant parameters such as the curvature of corner points, it is accomplished by shape similarity measurement in the visual concept, which is consistent with the process of the manual measurement method. The Hu moment [28], [29] is introduced to compare each extracted proppant with 20 particles in the standard template to determine the shape similarity. Finally, the sphericity and roundness of the most similar particle are taken as that of the proppant. The flow chart of this method is shown as that of FIGURE 2.

A. PROPPANT EXTRACTION

Before sphericity and roundness measurement, the main problem is how to extract each proppant accurately. Fuzzy connectedness algorithm [25]–[27] is a very effective method in image segmentation, and it is introduced to accomplish this task.

Fuzzy Connectedness: In an image I, we commence by computing the fuzzy adjacency $\rho_{i,j}$ between the pixels at $(x_i, y_i)$ and $(x_j, y_j)$ as follows:

$$
\rho_{i,j} = \begin{cases} 
\frac{1}{1 + \beta_1 d_{i,j}}, & d_{i,j} \leq 1 \\
0, & \text{otherwise}.
\end{cases}
$$

(1)

where $\beta_1$ is a nonnegative constant and $d_{i,j}$ is the Euclidean distance between the pixels at $(x_i, y_i)$ and $(x_j, y_j)$. The fuzzy affinity $\alpha_{i,j}$ between the pixels at $(x_i, y_i)$ and $(x_j, y_j)$ is defined as:

$$
\alpha_{i,j} = \frac{\rho_{i,j}}{1 + \beta_2 |I(x_i, y_i) - I(x_j, y_j)|}.
$$

(2)

where $\beta_2$ is a nonnegative constant and $I(x_i, y_i)$ is the gray value at $(x_i, y_i)$.

We denote the pixels $i$ and $j$ as adjacent pixels as long as the pixel $i$ is one of the four neighbors of the pixel $j$ and vice versa. According to the definitions of (1) and (2), $\alpha_{i,j}$ is nonzero as long as the pixels $i$ and $j$ are adjacent.

The seed region used as the prior knowledge within the proppant region in the proppant micrograph must contain many pixels. Suppose that $(x_0, y_0)$ is the coordinate of a certain pixel within the proppant region, we compute the fuzzy connectedness $\mu(x_0, y_0)(x, y)$ of one pixel at $(x, y)$ with respect to the selected initial pixel at $(x_0, y_0)$ as follows:

$$
\mu(x_0, y_0)(x, y) = \max_{p \in P} \left( \min_{(i,j) \in p} \alpha_{i,j} \right).
$$

(3)

where $P$ denotes the set of all possible paths between the pixel at $(x_0, y_0)$ and the pixel at $(x, y)$, and $p$ denotes an individual path between the pixel at $(x_0, y_0)$ and the pixel at $(x, y)$. Here, a path is a sequence of adjacent pixels, and $\alpha_{i,j}$ denotes the fuzzy affinity of a pair of adjacent pixels at $(x_i, y_i)$ and $(x_j, y_j)$ along the path $p$. The strength of a path is the smallest affinity of pairwise pixels along the path. The operation $\min$ in (3) computes the strength of a path $p$. The operation $\max$ in (3) selects the strongest path for characterizing the fuzzy connectedness.

The concept of fuzzy connectedness is derived from the theory of fuzzy sets. In the fuzzy set formulation, $(x_0, y_0), (x, y)$ is an element in a fuzzy set, and the fuzzy connectedness $\mu(x_0, y_0)(x, y)$ is its membership function characterizing the binary fuzzy relation. The theory of fuzzy sets elaborates many characteristics of fuzzy connectedness such as physical homogeneity, which plays an important role in our extraction scheme.

For concise presentation, when we refer to the fuzzy connectedness (value) of a pixel, we mean that the fuzzy connectedness (value) of the pixel with respect to the dot $(x_0, y_0)$ in
the seed region. The computation of (3) is implemented via dynamic programming, which has the optimal substructure property that a sub-path of a strongest path is itself a strongest path. The dynamic programming is in fact a recursive procedure such that the solution of a single subproblem is used multiple times for solving a larger problem. To this end, we introduce four concepts, i.e., farmed pixels, explorer pixels, detected pixels and reserved pixels. We introduce the four concepts in the scenario of the i-th round of recursion. The set of farmed pixels \( F_i \) refers to the pixels whose fuzzy connectedness values have been computed in previous rounds of recursions. The set of explorer pixels \( E_i \subseteq F_i \) refers to the pixels used for farming unfarmed pixels (i.e., those outside \( F_i \)). The set of detected pixels \( D_i \) refers to the unfarmed pixels which are adjacent to at least one of the explorer pixels \( E_i \). In the i-th round of recursion, the set of detected pixels \( D_i \) will be detected by the explorer pixels \( E_i \) and be farmed in terms of computing their fuzzy connectedness values based on the explorers’ fuzzy connectedness values. A pixel is used as an explorer pixel for only once, i.e., in one round of recursion. After being used as an explorer pixel, the role of the pixel as an explorer is immediately dismissed in the subsequent round of recursion, and this pixel does not become an explorer again in the following rounds of recursions. Because once a pixel has been used as an explorer, the fuzzy connectedness of its detected pixels (i.e., its four adjacent pixels) is computed. There is no need for it to become an explorer again since all its detected pixels have been farmed. Explorer pixels are changed for each round of recursion. The set of reserved pixels \( R_i \subseteq F_i \) refers to the pixels that have been farmed but have not been used as explorer pixels in previous rounds of recursions. It is obvious that \( E_i \subseteq R_i \). The set of explorer pixels \( E_i \) is selected from the set of reserved pixels \( R_i \), and those with the (common) maximum fuzzy connectedness value over all the reserved pixels are selected as explorer pixels.

We commence by considering the initial dots in the seed region as the sole explorer pixel \( E_1 \). In the initial round of recursion, \( F_1 = E_1 \) and \( R_1 = E_1 \). The fuzzy connectedness values for the detected pixels \( D_1 \) are initialized in terms of fuzzy affinities. Suppose \((x_1, y_1)\) is one pixel detected by the explorer pixel \((x_0, y_0)\). The fuzzy connectedness of \((x_1, y_1)\) is:

\[
\mu(x_0, y_0)(x_1, y_1) = \alpha_{01}. \tag{4}
\]

which forms one starting point for the recursive computations.

To commence the second round of recursion, the set of farmed pixels \( F_2 \) is formed by the union of \( F_1 \) and \( D_1 \) as follows:

\[
F_2 = F_1 \cup D_1. \tag{5}
\]

Accordingly, the set of reserved pixels \( R_2 \) is formed by the union of \((R_1 - E_1)\) and \( D_1 \) as follows:

\[
R_2 = (R_1 - E_1) \cup D_1. \tag{6}
\]

More generally, to commence the i-th round of recursion, the set of farmed pixels \( F_i \) is formed by the union of \( F_{i-1} \) and \( D_{i-1} \) as follows:

\[
F_i = F_{i-1} \cup D_{i-1}. \tag{7}
\]

Accordingly, the set of reserved pixels \( R_i \) is formed by the union of \((R_{i-1} - E_{i-1})\) and \( D_{i-1} \) as follows:

\[
R_i = (R_{i-1} - E_{i-1}) \cup D_{i-1}. \tag{8}
\]

\( E_i \) is selected from \( R_i \) as those with the maximum fuzzy connectedness value. Specifically, for every \( e_i \subseteq E_i \), the fuzzy connectedness \( \mu(x_0, y_0)(x_e, y_e) \) is the same with one another because the explorer pixels in \( E_i \) have the common maximum fuzzy connectedness value \( \mu_{E_i} \) over all the reserved pixels \( r_i \in R_i \). The maximum fuzzy connectedness value \( \mu_{E_i} \) is computed as follows:

\[
\mu_{E_i} = \max_{r_i \in R_i} \mu(x_0, y_0)(x_{r_i}, y_{r_i}). \tag{9}
\]

Suppose that a detected pixel \( d_i \in D_i \) at \((x_d, y_d)\) has an affinity \( \alpha_{e_i,d_i} \) with respect to an explorer pixel \( e_i \). Its fuzzy connectedness is computed as follows:

\[
\mu(x_0, y_0)(x_d, y_d) = \min \left\{ \max_{r_i \in R_i} \mu(x_0, y_0)(x_{r_i}, y_{r_i}), \max_{e_i \in E_i} \alpha_{e_i,d_i} \right\}.
\]

Solving the subproblems (9) and (10) results in fuzzy connectedness values for all pixels in \( D_i \). In terms of (9) and (10), based on the fuzzy connectedness values of pixels in \( E_i \), \( E_i \) forms \( D_i \) by computing the fuzzy connectedness of every pixel in \( D_i \). This completes the i-th round of recursion.

To commence the \((i + 1)\)-th round of recursion, the set of farmed pixels \( F_{i+1} \) are formed by the union of \( F_i \) and \( D_i \) as follows:

\[
F_{i+1} = F_i \cup D_i. \tag{11}
\]

Accordingly, the set of reserved pixels \( R_{i+1} \) is formed by the union of \((R_i - E_i)\) and \( D_i \) as follows:

\[
R_{i+1} = (R_i - E_i) \cup D_i. \tag{12}
\]

Then the \((i + 1)\)-th round of recursion operates such that \( E_{i+1} \) is selected from \( R_{i+1} \), and \( E_{i+1} \) farms \( D_{i+1} \).

**Extraction Procedure:** The micrographs of proppants always have some shortcomings, such as some non-proppant targets, shown in FIGURE 3 which includes 23 proppants, one hole inherent of the placement plane and the green numbers that are marked as the serial number of each proppant. Our purpose is to provide candidate seed regions of each proppant for fuzzy connectedness algorithm to obtain each proppant accurately. The micrographs of proppants have 3 channels including RGB, we update (2) to (13), shown at the bottom of the next page, through taking all values of 3 channels. There are several steps of the proppant extraction, shown in below:

Step 1. In the proppant micrograph, based on the difference of RGB color range between proppant and the hole, three
different RGB thresholds are set separately to mark the region of hole. After extracting the region that meets the proppant threshold range, set all pixels in the region to 1, and all pixels in the rest regions to 0. The result of FIGURE 3 is shown in FIGURE 4, in which we can find that there is nothing in the center of the hole.

Step 2. By using the connected component labeling method in statistics theory, some small regions with a few pixels that are equivalent to 1 are removed. Based on the difference whether the center region has many pixels equivalent to 1 or not, the hole without a proppant is eliminated and the proppants regions are all filled as shown in FIGURE 5. Then, the central region of each proppant is selected as the candidate seed region of the fuzzy connectedness algorithm, which is denoted by a colored rectangle shown in FIGURE 6.

Step 3. Apply the fuzzy connectedness algorithm in the whole image based on all seed regions. The fuzzy connectedness map is shown in FIGURE 7. For each proppant, we calculate the histogram of the fuzzy connectedness map in its region in FIGURE 5, then we find a suitable fuzzy

$$
\alpha_{i,j} = \frac{\rho_{ij}}{1 + \beta_2 \sqrt{(I_R(x_i,y_i) - I_R(x_j,y_j))^2 + (I_G(x_i,y_i) - I_G(x_j,y_j))^2 + (I_B(x_i,y_i) - I_B(x_j,y_j))^2}}
$$

(13)
connectedness threshold. There are two contents to find a suitable threshold. The first one is to find the first non-zero value with the biggest amount. The second one is to find another non-zero value smaller than the first non-zero value with the second biggest amount, and the second non-zero value is the threshold we need. An example of the threshold is shown in the red circle in FIGURE 8 and it is 0.8902. Based on the different fuzzy connectedness thresholds of each proppant, all the edges of proppants will be extracted from the fuzzy connectedness map.

Step 4. Based on the edges of all the proppants, fill their inner holes to lay a foundation for the subsequent similarity measurement.

B. SHAPE SIMILARITY MEASUREMENT

In the standard template proposed by Krumbein in API RP60, 20 particles are divided into 4 rows and 5 columns. Each row is corresponding to a sphericity value and each column is corresponding to a roundness value. In this section, the shape similarity between each proppant extracted and each particle in the standard template is discussed based on Hu moment [28].

Hu moment is one of image moments and is derived from the theory of probability [28]. There are many features to describe the distribution of random variables. To obtain moment invariants, Hu [29] applied the theory of moments to image analysis. In his study, the two-dimensional \((i+j)\)-th order moments of a density distribution function \(\rho(x, y)\) were defined in terms of Riemann integrals as:

\[
M_{ij} = \int_\zeta x^i y^j \rho(x, y) dxdy \quad i, j = 0, 1, 2, \cdots ,
\]

where, \(\zeta\) is the image region and \(\rho(x, y)\) is the gray value of each pixel at the position with coordinate \((x, y)\). Because (14) cannot be used to compute the discrete moment directly, we change it to (15) which is called the original moment of the image.

\[
M_{ij} = \sum_{x} \sum_{y} x^i y^j I(x, y)
\]

where \(i\) and \(j\) appear as powers of coordinates \((x, y)\), and their values are integers. The original moment is related to the position of image pixels and can reflect some shape information of the target in the image to a certain extent. Meanwhile, the original moment is used to calculate the centroid of the image as follows.

\[
\begin{align*}
\overline{x} &= \frac{M_{10}}{M_{00}} \\
\overline{y} &= \frac{M_{01}}{M_{00}}.
\end{align*}
\]

If we take (16) into (15), the central moment of image is formulated as follows.

\[
\mu_{ij} = \sum_{x} \sum_{y} (x - \overline{x})^i (y - \overline{y})^j I(x, y).
\]

This kind of image moment \(\mu_{ij}\) has translation invariance. No matter where the target region is in the image, the shape is the same, its central moment must be the same. Furthermore, defining the \((i+j)\)-th order normalized central moment of image:

\[
\eta_{ij} = \frac{\mu_{ij}}{\mu_{00}^{(i+j)/2+1}}.
\]

The normalized central moment \(\eta_{ij}\) has translation and scale invariance, but does not have rotation invariance. Hu [29] obtained a set of moment invariants with translation, rotation and scale-invariant features by linearly combining the lower order normalized central moments, which is called Hu moment and includes 7 expressions:

\[
\begin{align*}
h_0 &= \eta_{20} + \eta_{02} \\
h_1 &= (\eta_{20} - \eta_{02})^2 + 4\eta_{11}^2 \\
h_2 &= (\eta_{30} - 3\eta_{12})^2 + (3\eta_{21} - \eta_{03})^2 \\
h_3 &= (\eta_{30} + \eta_{12})^2 + (\eta_{21} + \eta_{03})^2 \\
h_4 &= (\eta_{30} - 3\eta_{12})(\eta_{30} + \eta_{12})[3(\eta_{30} + \eta_{12})^2 - 3(\eta_{21} + \eta_{03})^2] \\
&\quad + (3\eta_{21} - \eta_{03})[3(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2] \\
h_5 &= (\eta_{20} - \eta_{02})(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2 + 4\eta_{11}(\eta_{30} + \eta_{12}) (\eta_{21} + \eta_{03}) \\
h_6 &= (3\eta_{21} - \eta_{03})(\eta_{30} + \eta_{12})[\eta_{30} + \eta_{12}]^2 - 3(\eta_{21} + \eta_{03})^2 \\
&\quad + (\eta_{30} - 3\eta_{12})(\eta_{21} + \eta_{03})[3(\eta_{30} + \eta_{12})^2 - (\eta_{21} + \eta_{03})^2].
\end{align*}
\]

In (19), the first six parameters are proved to have translation invariance, rotation invariance, scale invariance and flip invariance, while the 7-th parameter is related to image flip. Through the actual image experiment, it is found that the seven parameters have a very large distribution range, and the large magnitude difference is not conducive to comparison. Therefore, this paper takes the logarithm of these seven parameters to make them distributed in the same range, namely:

\[
H_i = -\text{sign}(h_i)\log_{10}|h_i|.
\]

where, the function \(\text{sign}(x)\) is the sign function, if \(x > 0\), it returns 1, if \(x < 0\), it returns -1, and if \(x = 0\), it returns 0.
The experiments demonstrate that when the shape of the two target regions in the image is similar, the first six parameters of Hu moment have little difference. Especially, when the shape of the two regions is similar, but they are mirror images, the absolute value of the 7-th parameter has little difference, but the sign is opposite. According to the characteristics of seven parameters in Hu moment, the following measures are defined to measure the difference $D(A, B)$ between shapes $A$ and $B$:

$$D(A, B) = \sqrt{\sum_{i=0}^{5} (H_B^i - H_A^i)^2 + (|H_B^6| - |H_A^6|)^2}.$$  \hspace{1cm} (21)

The greater the value of $D(A, B)$, the greater the difference between the two shapes $A$ and $B$, and vice versa.

**II. EVALUATION**

To present the effectiveness of the proposed method, a few actual proppants made of different materials are used for experiments as shown in FIGURE 3, FIGURE 9, FIGURE 10 and FIGURE 11. In FIGURE 3, all proppants are made of ceramics, in FIGURE 9 most proppants are made of ceramics except No.10, in FIGURE 10 most proppants are made of quartz sand except No. 22, and in FIGURE 11 all proppants are made of quartz sand. In the measurement procedure, a perforated metal plate is used as the placement plane to prevent the adhesion between the proppants. If there is no proppant placing upon the hole, it appears hole in FIGURE 3. According to the standard proppant measurement procedure, we have made two kinds of comparative experiments. The first one is proppant extraction experiments of different methods. The second one is the sphericity and roundness determination experiments of different methods from several scholars. Our experimental platform is a computer with Windows10 OS, I7 CPU, RAM of 8GB, SSD of 256 GBytes. We use Matlab R2019b for the simulations.

**A. PROPPANT EXTRACTION EXPERIMENT**

For proppant extraction, it is found that the threshold method, such as Otsu method \[30\], is effective to some extent, and the level set method \[31\] is an excellent method of target segmentation. The proppant extraction results of FIGURE 3 based on Otsu, level set and fuzzy connectedness are shown in FIGURE 12. The proppant extraction results of FIGURE 9 based on different methods are shown in FIGURE 13. The proppant extraction results of FIGURE 10 based on different methods are shown in FIGURE 14. The proppant extraction results of FIGURE 11 based on different methods are shown in FIGURE 15.

From the proppant extraction experiments both for proppants of quartz sand and proppants of ceramics, the results of the Otsu method or level set method contain many regions that do not belong to proppants, and the fuzzy connectedness
Figure 12. Different proppant extraction results of three methods of Figure 3.

(a) Extraction result of Otsu method of Figure 3.

(b) Extraction result of level set method with 3000 iterations of resized Figure 3 with coefficient equivalent to 0.1.

(c) Extraction result of fuzzy connectedness method of Figure 3.

Figure 13. Different proppant extraction results of three methods of Figure 9.

(a) Extraction result of Otsu method of Figure 9.

(b) Extraction result of level set method with 3000 iterations of resized Figure 9 with coefficient equivalent to 0.1.

(c) Extraction result of fuzzy connectedness method of Figure 9.

Method has a better performance. Although the result of the fuzzy connectedness method is worse than that of the former algorithm [24], the reason is that the algorithm [24] uses the subtraction method of two images. The first image is without proppants and the second one is with proppants, meanwhile the placement plane should be fixed during image...
It is inconvenient that we constantly replace the different proppants during the measurement process or the placement plane is moved carelessly during the process. This results in low efficiency or errors of the subtraction method in extracting proppant.

**B. SPHERICITY AND ROUNDNESS DETERMINATION EXPERIMENT**

The comparison experimental results of different proppants with different methods include manual measurement method,
Pei’s method [16], the method [24] proposed by the author in 2019 named Lyu2019, Zheng’s method [21], [22](based on fuzzy connectedness extraction result and $s_{WL}$ is selected as the sphericity) and the proposed method in this paper.

For proppants made of ceramics in FIGURE 3 and FIGURE 9, the Hu moment distance between the former 4 proppants and 20 particles are shown in TABLE 1 and TABLE 2, and we find that all 4 proppants are the most similar to the particle with serial number 5 in the standard template. According to the minimum Hu moment distance between each proppant and 20 particles in the template, the sphericity and roundness determination results are shown in TABLE 3 and TABLE 4 with the results of other methods. The time of the last row is starting from image processing, excluding the acquisition of proppant micrographs.

**TABLE 1. Hu moment distance between 4 proppants and 20 particles of FIGURE 3.**

| Particle number in template | Proppant number in FIGURE 3 | Hu moment distance |
|----------------------------|----------------------------|--------------------|
| 1                          | 10.2411                    | 12.9429            |
| 2                          | 9.1954                     | 11.9115            |
| 3                          | 11.1915                    | 13.5960            |
| 4                          | 7.2169                     | 9.9187             |
| 5                          | 6.8636                     | 7.1563             |
| 6                          | 16.0735                    | 18.7753            |
| 7                          | 18.6508                    | 21.3526            |
| 8                          | 12.6352                    | 14.2057            |
| 9                          | 22.9173                    | 25.6191            |
| 10                         | 16.7352                    | 19.4370            |
| 11                         | 25.1346                    | 27.8364            |
| 12                         | 20.4989                    | 23.2007            |
| 13                         | 27.6794                    | 30.3812            |
| 14                         | 18.3273                    | 21.0291            |
| 15                         | 24.9025                    | 27.6043            |
| 16                         | 21.2718                    | 23.9736            |
| 17                         | 22.7128                    | 28.2948            |
| 18                         | 25.5930                    | 30.0657            |
| 19                         | 27.3639                    | 27.9043            |
| 20                         | 25.2025                    | 21.3526            |

For proppants in FIGURE 10 and FIGURE 11, the Hu moment distance between the former 4 proppants for example and 20 particles are shown in TABLE 5 and TABLE 6. We find that 4 proppants are the most similar to different particles in the template. And according to the minimum Hu moment distance between each proppant and 20 particles in the template, the sphericity and roundness determination results are shown in TABLE 7 and TABLE 8 with the results of other methods. Similarly, the time of the last row is starting from image processing, excluding the acquisition of proppant micrographs.

According to [24], two error functions are used to describe the closeness of sphericity and roundness by the proposed method to the manual measurement method respectively, shown in (22) and (23).

$$SE = \text{abs}(S_m - S_i). \tag{22}$$

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**TABLE 2. Hu moment distance between 4 proppants and 20 particles of FIGURE 9.**

| Particle number in template | Proppant number in FIGURE 9 | Hu moment distance |
|-----------------------------|-----------------------------|--------------------|
| 1                           | 26.8925                     | 28.4730            |
| 2                           | 33.1586                     | 34.5089            |
| 3                           | 19.339                      | 19.6344            |
| 4                           | 19.6803                     | 20.0153            |
| 5                           | 17.3562                     | 18.4238            |
| 6                           | 25.5015                     | 27.0717            |
| 7                           | 24.8959                     | 26.4617            |
| 8                           | 26.9888                     | 28.5536            |
| 9                           | 24.4865                     | 26.0451            |
| 10                          | 25.8079                     | 27.3773            |
| 11                          | 23.6988                     | 25.2457            |
| 12                          | 18.2059                     | 18.7464            |
| 13                          | 18.0326                     | 18.6638            |
| 14                          | 23.3459                     | 24.8876            |
| 15                          | 25.3727                     | 26.9292            |
| 16                          | 24.2508                     | 25.7984            |
| 17                          | 17.9251                     | 18.6310            |
| 18                          | 24.1199                     | 25.6671            |
| 19                          | 23.8322                     | 25.3734            |
| 20                          | 24.1841                     | 25.7306            |

**TABLE 3. Sphericity and roundness determination results using different methods for FIGURE 3.**

| Proppant number | Manual measurement method | Pei’s method | Lyn2019 method | Zheng’s method |
|-----------------|---------------------------|--------------|----------------|----------------|
| 1               | 0.9/0.9                   | 0.9/0.9      | 0.96/0.9       | 0.9/0.9       |
| 2               | 0.9/0.9                   | 0.9/0.9      | 0.97/0.9       | 0.95/0.88     |
| 3               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.97/0.61     |
| 4               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.97/0.64     |
| 5               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.83/0.59     |
| 6               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.98/0.71     |
| 7               | 0.9/0.9                   | 0.9/0.9      | 0.95/0.87      | 0.99/0.69     |
| 8               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.99/0.68     |
| 9               | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.99/0.68     |
| 10              | 0.9/0.9                   | 0.9/0.9      | 0.94/0.89      | 0.97/0.79     |
| 11              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.91/0.75     |
| 12              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.90/0.65     |
| 13              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.97/0.84     |
| 14              | 0.9/0.9                   | 0.9/0.9      | 0.96/0.9       | 0.95/0.67     |
| 15              | 0.9/0.9                   | 0.9/0.9      | 0.97/0.9       | 0.92/0.71     |
| 16              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.94/0.92     |
| 17              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.96/0.79     |
| 18              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.95/0.86     |
| 19              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.95/0.68     |
| 20              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.94/0.52     |
| 21              | 0.9/0.9                   | 0.9/0.9      | 0.97/0.9       | 0.98/0.75     |
| 22              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.96/0.57     |
| 23              | 0.9/0.9                   | 0.9/0.9      | 0.98/0.9       | 0.99/0.79     |

Time(s) to about 70 13.5 14.3 12.2 15.2
\[ RE = |R_m - R_i| \]  

where \( SE \) indicates the sphericity error between manual measurement method \( S_m \) and other methods \( S_i \) including Pei’s method, Lyu2019 method, Zheng’s method and the proposed method. \( RE \) indicates the roundness error between manual measurement method \( R_m \) and other methods \( R_i \) including
Pei’s method, Lyu2019 method, Zheng’s method and the proposed method. Errors of sphericity and roundness determination in TABLE 3, TABLE 4, TABLE 7 and TABLE 8 between the manual method and other methods are shown in TABLE 9, TABLE 10, TABLE 11 and TABLE 12 respectively, where the results of Lyu2019 method and Zheng’s method have been
converted into the values of the standard template according to the principle of proximity [24].

From TABLE 9 and TABLE 10, for proppants made of ceramics, all the four methods get the results of sphericity very close to that of the manual measurement method with small error or even no error, and for roundness, only Zheng’s method has a bigger error. But for proppants made of quartz sand, from TABLE 11 and TABLE 12, all the four methods have errors in the results compared with manual measurement method for some proppants. The difference is that Zheng’s method and Pei’s method have bigger errors, while the Lyu2019 method and the method proposed in this paper have smaller errors, which are almost the same.

### C. EXPERIMENTAL RESULTS ANALYSIS

1) For proppant extraction, the advantages of proppant extraction based on fuzzy connectedness can be listed as follows. (a) There is no human interaction in the proppant extraction process. (b) The final extraction results can be reproduced, which is different from level set method that different initialization and iterations lead to different results. (c) It has higher accuracy because the extracted edges of proppants mostly coincide with the actual proppant edges.

2) For sphericity and roundness determination, the novelty of shape similarity measurement based on Hu moment includes: (a) it is in line with the manual measurement process which is based on shape comparison, (b) the method has higher accuracy in sphericity and roundness determination because the results have smaller errors compared with that of the manual measurement method.

### IV. CONCLUSIONS AND DISCUSSION

Fracturing proppants play an important role in oil and gas production. A method has been designed to determine the sphericity and roundness of fracturing proppant in this paper. In this method, the fuzzy connectedness map has been accomplished based on many candidate seed regions which are generated by some pre-processing procedures including color characteristics thresholds and connected component labeling. Each proppant has been extracted by a suitable fuzzy connectedness threshold using a histogram method. For each extracted proppant, the method of shape similarity measurement based on Hu moment has been used to find the most similar particle from 20 particles of the standard template, and the corresponding sphericity and roundness are used as that of the proppant. Finally, proppants made of ceramic and quartz sand have been used in the comparison measurement experiments. The results show that the method designed in this paper has a better performance than Otsu method and level set method in proppant extraction. In sphericity and roundness measurement, the proposed method has a higher accuracy which is basically consistent with the manual measurement method. At the same time, the proposed method will reduce human labor and improve the efficiency of the measurement process. However, at present, there are still some defects in this method. The first one is the selection of proppant extraction methods. Although the fuzzy connectedness method has a higher accuracy in proppant extraction, it still exists some errors in edges extracted due to the fact that the color of proppants made of ceramics is close to that of holes in the placement plane. In the future work, we plan to solve this in two directions: (1) trying some segmentation methods in frequency domain, (2) placing a circle of LED strips under the placement plane to change the color of holes. The second shortcoming is that because the number of particles in the standard template is limited and the fracturing proppant materials and shapes are diverse, the shape similarity measurement based on Hu moment is sensitive to distance. For example, for the proppant with No. 2 in FIGURE 11, the similarity distance between it and some particles in the standard template is only slightly different, which may cause the measurement errors. In the future work, the method of generative adversarial networks [32] and neural networks [33]–[35] will be considered to approach the shape between the proppant and the particles in the standard template, and a more effective method of shape similarity measurement will be investigated.

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REFERENCES

[1] Baidu Encyclopedia, Fracturing Proppant. Accessed: Nov. 25, 2019. [Online]. Available: https://baike.baidu.com

[2] Specification and Recommended Testing Practice For Proppants Used in Hydraulic Fracturing Operations, Petroleum and Natural Gas Industry Standard of the People’s Republic of China, Beijing, China, 2006.

[3] H. Wadell, “Volume shape, and roundness of rock particles,” J. Geol., vol. 40, no. 5, pp. 443–451, 1932.

[4] W. C. Krumbein, “Measurement and geological significance of shape and roundness of sedimentary particles,” SEPM J. Sedimentary Res., vol. 11, pp. 64–72, 1941.

[5] S. Arasan, E. Yener, F. Hattatoglu, S. Akbulut, and S. Hasiloğlu, “The relationship between the fractal dimension and mechanical properties of asphalt Concrete,” Int. J. Civil Struct. Eng., vol. 1, no. 2, pp. 165–170, 2010.

[6] U. Gori and M. Mari, “The correlation between the fractal dimension and internal friction angle of different granular materials,” Soils Found., vol. 41, no. 6, pp. 17–23, Dec. 2001.

[7] Y. F. Xu and D. A. Sun, “Correlation of surface fractal dimension with fractional angle at critical state of sands,” Géotechnique, vol. 55, no. 9, pp. 691–695, Nov. 2005.

[8] S. Arasan, S. Akbulut, and A. S. Hasiloğlu, “The relationship between the fractal dimension and shape properties of particles,” KSCE J. Civ. Eng., vol. 15, no. 7, pp. 1219–1225, Sep. 2011.

[9] W. Q. Pan, L. Yao, and W. T. Ji, “A new method of measurement of proppant sphericity and roundness,” Trans. Autom. Appl., vol. 34, no. 3, pp. 91–96, 2015.

[10] T. Andersson, “Estimating particle size distributions based on machine vision,” Ph.D. dissertation, Dept. Comput. Sci. Elect. Eng., Lule Univ. Technol., Luleå, Sweden, 2010.

[11] J. M. R. Fernlund, “Image analysis method for determining 3-D shape of coarse aggregate,” Cement Concrete Res., vol. 35, no. 8, pp. 1629–1637, Aug. 2005.

[12] E. T. Bowman, K. Soga, and W. Drummond, “Particle shape characterisation using Fourier descriptor analysis,” Géotechnique, vol. 51, no. 6, pp. 545–554, Aug. 2001.

[13] X. Zhang, “Measurement and analysis of proppant sphericity and roundness,” J. Liaoning Tech. Univ., no. 6, pp. 29–31,2006.

[14] M. Juan Rodriguez, J. Johansson, and T. Edeskáir, “Particle shape determination by two-dimensional image analysis in geotechnical engineering,” in Proc. Nordic Conf. Soil Mech. Geotechnical NGM, vol. 2012, pp. 207–218.

[15] M. Juan Rodriguez, T. Edeskáir, and S. Knutsen, “Particle shape quantities and measurement techniques-a review,” Electron. J. Geotechnical Eng., vol. 18, pp. 169–198, Dec. 2013.

[16] P. Runyou, X. Caili, H. Kexian, and L. Xinrong, “Research on measurement of sphericity and roundness of proppant,” Electron. Meas. Technol., vol. 38, no. 1, pp. 21–24, 2015.

[17] Y. Takashimizu and M. Iiyoshi, “New parameter of roundness R: Circularity corrected by aspect ratio,” Prog. Earth Planet. Sci., vol. 3, no. 1, p. 2, Dec. 2016.

[18] W. J. Wang, Y. J. Xu, and H. T. Li, “Calculation of roundness of limestone particles based on binary image processing,” China Water Transp., vol. 16, no. 8, pp. 330–332, 2016.

[19] J.-F. Zhang, J.-B. Ye, J.-S. Chen, and S.-L. Li, “A preliminary study of measurement and evaluation of breakstone grain shape,” Rock Soil Mech., vol. 37, no. 2, pp. 343–349, 2016.

[20] H. Fang, “Automatic Fourier-descriptor-based generation of particle shape of sandy soil,” Geol. J. China Univ., vol. 24, no. 4, pp. 604–612, 2018.

[21] J. Zheng and R. D. Hryciw, “Traditional soil particle sphericity, roundness and surface roughness by computational geometry,” Géotechnique, vol. 65, no. 6, pp. 494–506, Jun. 2015.

[22] J. Zheng and R. D. Hryciw, “Roundness and sphericity of soil particles in assemblies by computational geometry,” J. Comput. Civil Eng., vol. 30, no. 6, Nov. 2016, Art. no. 04016021.

[23] R. D. Hryciw, J. Zheng, and K. Shetler, “Particle roundness and sphericity from images of assemblies by chart estimates and computer methods,” J. Geotechnical Geoenvironmental Eng., vol. 142, no. 9, Sep. 2016, Art. no. 04016038.

[24] X. Lyu, F. Liu, P. Ren, and C. Grecos, “An image processing approach to measuring the sphericity and roundness of fracturing proppants,” IEEE Access, vol. 7, pp. 16078–16087, 2019.

[25] J. K. Udupa and P. K. Saha, “Fuzzy connectedness and image segmentation,” Proc. IEEE, vol. 91, no. 10, pp. 1649–1669, Oct. 2003.

[26] J. Lindblad, N. Saldojo, H. Sarve, B. Johansson, and G. Borgefor, “Improved quantification of bone remodelling by utilizing fuzzy based segmentation,” Scandian. Conf. Image Anal. Springer-Verlag, pp. 750–759, 2009.

[27] P. Ren, M. Xu, Y. Yu, F. Chen, X. Jiang, and E. Yang, “Energy minimization with one dot fuzzy initialization for marine oil spill segmentation,” IEEE J. Ocean. Eng., vol. 44, no. 4, pp. 1102–1115, Oct. 2019.

[28] Z. Fu, L. Fan, Z. Yu, and K. Zhou, “A moment-based shape similarity measurement for areal entities in geographical vector data,” ISPRS Int. J. Geo-Information, vol. 7, no. 6, p. 208, 2018.

[29] M.-K. Hu, “Visual pattern recognition by moment invariants,” IEEE Trans. Inf. Theory, vol. 8, no. 2, pp. 179–187, Feb. 1962.

[30] N. Otro, “A threshold selection method from gray-level histograms,” IEEE Trans. Syst., Man, Cybern., vol. 9, no. 1, pp. 62–66, Jan. 1979.

[31] C. Li, C. Xu, C. Gui, and M. D. Fox, “Level set evolution without re-initialization: A new variational formulation,” in Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit. (CVPR05), 2005, pp. 430–436.

[32] J. I. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, and S. O’zair, “Generative adversarial networks,” in Proc. Adv. Neural Process. Syst., vol. 3, 2014, pp. 2672–2680.

[33] S. Wen, H. Wei, Z. Yan, Z. Guo, Y. Yang, T. Huang, and Y. Chen, “Memristor-based design of sparse compact convolutional neural network,” IEEE Trans. Netw. Sci. Eng., early access, Aug. 14, 2019, doi: 10.1109/TSNE.2019.2934357.

[34] B. Sun, S. Wen, S. Wang, T. Huang, Y. Chen, and P. Li, “Quantized synchronization of memristive neural networks with time-varying delays via super-twisting algorithm,” Neurocomputing, vol. 380, pp. 133–140, Mar. 2020.

[35] Y. Cao, S. Wang, Z. Guo, T. Huang, and S. Wen, “Synchronization of memristive neural networks with leakage delay and parameters mismatch via event-triggered control,” Neural Netw., vol. 119, pp. 178–189, Nov. 2019.

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