Volume calculation of goaf based on 3D scanning

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Abstract. The goaf formed by underground mining poses a great safety hazard to the production of the mining area. The accurate calculation of goaf volume is the data basis for the filling and blasting of the goaf, and it also has certain reference significance for the monitoring of collapse accidents. In this paper, the data detected by the 3D ranging scanner is used to build a network model on the self-developed 3D modeling platform, and the network model is divided into the smallest triangular grid. The algorithm uses the scanner's laser probe as the common point, accumulates all the minimum tetrahedral volumes constructed by the common point and the smallest triangular grid, and completes the accurate solution of the total volume of the scanned goaf. Experiments and practical applications show that the volumetric algorithm has high accuracy, and has universal applicability to the volume calculation of similar types of space scanning equipment.

1. Introduction
The mined-out area left over by underground mine tunnel mining has become one of the main factors threatening safe production. With the transformation of underground mining to open-pit mining, the original goaf has caused serious damage to the stability of the new open-pit pit[1]. Accurately detecting and calculating the volume of the original mined-out area is of great significance to the normal production of the mining area and the safe handling of the mined-out area[2-3].

To deal with the hidden dangers of the goaf, many scholars have researched its volume detection. The photogrammetry method uses beam adjustment to process downhole photographic data, obtains the discrete points of the goaf trend through function interpolation, and uses reintegration to obtain the goaf volume. Not all goaf allow personnel to enter, and this method has great limitations [4]. In the literature [5], Wang Quande adopted a method of calculating the model volume only based on the set of triangle faces of the triangulation model. First, specify the projection plane, accumulate the signed volume of each triangle patch and its projection on the projection plane to form the signed volume of the convex pentahedron to obtain the volume of the entire space. However, the judgment of the triangular topological relationship in this method is extremely complicated, and the projection surface is also difficult to find. Currently, the most widely used method is the section method, which divides the space into several small sections. The volume of a single section can be obtained according to the section's cross-sectional area and vertical distance, and the entire space volume can be obtained by cumulative calculation [6-7]. The three-dimensional modeling platform in the laboratory originally used the section method, which is very effective for the volume calculation of the regular space, but the shape of the mined-out area is extremely complicated, which will cause large errors.

In this paper, the goaf contour network model is constructed based on the data collected by 3d ranging scanner and segmented by a tetrahedron or quadric pyramid. Establish a suitable spatial coordinate
system, and locate the coordinates of the scattered points of the goaf model. According to the difference of the tetrahedral segmentation method, the whole goaf model is divided into three parts. By accumulating the volume of the tetrahedron, the three parts of the volume calculation are completed in sequence, and the total volume of the mined-out area is finally calculated.

2. Data measurement and processing of 3D range scanner

2.1. Measuring principle

The 3D ranging scanner uses the principle of laser ranging to perform 3D scanning of the inside of the goaf [8-9]. The specific measurement steps are: drill holes on the top of the goaf area, install the scanner and initialize the settings; drive the distance measuring probe to perform three-dimensional scanning, and the range of up and down inclination of the probe is 0°-144°. Every time the inclination angle is raised by 3.6°, it rotates 360° horizontally to perform a range-finding scan. For every 3.6° rotation, range-finding data is collected and stored synchronously to the host computer. The data storage format is \((\beta, \alpha, r)\), \(\beta\) is the inclination angle of the probe, \(\alpha\) is the rotation angle of the probe, and \(r\) is the measurement distance of the probe.

![Figure 1. Working principle of 3D ranging scanner](image)

All measured data points are scattered points, and the goaf network model needs to be imaged on the goaf 3D modeling platform [10-11]. The construction of the smallest triangle mesh is an important prerequisite to ensure the accuracy of the volume calculation results. The construction method of the goaf model is as follows: The 100 points with the same inclination angle are connected in sequence, and the 81 points with the rotation angle are connected in sequence to form a closed network model of the goaf. The minimum triangular grid is constructed based on the goaf model [12]. The methods and requirements are as follows: 1) In order to ensure accuracy, each triangle mesh must be the smallest triangle mesh that can be constructed, and no overlap occurs on the goaf network model; 2) Each edge has and only two triangular meshes in common. The minimum triangular mesh construction of part of the model is shown in Figure 2.
3. Volume algorithm of mined-out area

3.1. Volume calculation of the smallest tetrahedron

The scheme takes the laser emission point of the ranging probe as the origin \( O \). The vertical downward (\( \beta = 0^\circ \)) direction is the positive direction of the \( z \)-axis to establish a spatial rectangular coordinate system. A spatial rectangular coordinate system is established. Coordinate positioning of all scattered points of the goaf network model [13]:

\[
\begin{align*}
    x &= r \cdot \sin(90^\circ - \beta) \cos \alpha \\
    y &= r \cdot \sin(90^\circ - \beta) \cos \alpha \\
    z &= r \cdot \cos(90^\circ - \beta)
\end{align*}
\]  

(1)

Find a common point in the goaf model, which forms the smallest tetrahedron with all the smallest triangle meshes. According to the measurement principle of the scanner, the origin \( O \) is selected as the common point, all the smallest tetrahedrons will not have overlapping parts, and the volume calculation of the smallest tetrahedron is also very easy. The tetrahedron formed by the triangular mesh \( \Delta MNL \) and \( O \) points is shown in Figure 3.

![Figure 3. A tetrahedral consisting of \( \Delta MNL \) and \( O \)](image)

Suppose the coordinates of the three points \( M, N, L \) are \( M(x_1, y_1, z_1), N(x_2, y_2, z_2), L(x_3, y_3, z_3) \), the volume of the tetrahedron OMNL is [14-16]:

\[
V_{OMNL} = \frac{1}{6} \left| \overrightarrow{OM}, \overrightarrow{ON}, \overrightarrow{OL} \right| = \frac{1}{6} \left| \begin{array}{ccc}
    x_1 & x_2 & x_3 \\
    y_1 & y_2 & y_3 \\
    z_1 & z_2 & z_3
\end{array} \right|
\]  

(2)

3.2. The volume calculation process of the goaf

The tetrahedron construction ideas of the entire goaf network model are not completely consistent. The volume calculation will be divided into three parts: the first part is the area scanned by the probe inclination \( \beta \leq 3.6^\circ \), and the volume is represented by \( V_{\beta \leq 3.6^\circ} \); the second part is the area where the inclination range is \( 3.6^\circ < \beta \leq 144^\circ \) and the volume is represented by \( V_{3.6^\circ < \beta \leq 144^\circ} \); the remaining area is the
third part, and the volume is represented by $V_{\beta=144^\circ}$. The schematic diagram of the vertical section of the area division is shown in Figure 4.

Figure 4. Schematic diagram of vertical section

Suppose the scatter points collected at the inclination angle $\beta=0^\circ$ are $k$, and the i-th measuring point at $\beta=3.6^\circ$ is $a$. $O_k$ is the common edge of all tetrahedrons in the area. The solid line is the smallest triangle mesh in the goaf model topology, and the dashed line is the auxiliary line for constructing the tetrahedron. The construction of the tetrahedron in the scanning area of $\beta \leq 3.6^\circ$ is shown in Figure 5.

Figure 5. Construction of tetrahedron in $\beta \leq 3.6^\circ$

Use $V_{\beta=3.6^\circ}$ to represent the volume of the i-th tetrahedron in the region of $\beta \leq 3.6^\circ$.

$$V_{\beta\leq3.6^\circ} = \sum_{i=1}^{100} V_{a-i} \quad (i = 1, 2, 3 \ldots 100) \quad (3)$$

Suppose the i-th measuring point with an inclination angle $\beta=7.2^\circ$ is $b$, and the origin $O$ is the common vertex of all quadrangular pyramids in the region of $3.6^\circ < \beta \leq 7.2^\circ$. Connect $a_{i+1}$ and $b_i$, and $a_i$ and $b_{100}$ to construct the smallest triangle mesh. The construction of the tetrahedron in the scanning area of $3.6^\circ < \beta \leq 7.2^\circ$ is shown in Figure 6.

Figure 6. Construction of tetrahedron in $3.6^\circ < \beta \leq 7.2^\circ$

Use $V_{\beta\leq7.2^\circ}$ to represent the volume of the i-th quadrangular pyramid in the $3.6^\circ < \beta \leq 7.2^\circ$ area. Each quadrangular pyramid is composed of the two smallest tetrahedrons, and the sum of the volume of the two tetrahedrons is the volume of the quadrangular pyramid.
The volume of another goaf outside $3.6^\circ < \beta \leq 7.2^\circ$ area can be solved by $V_{3.6^\circ < \beta \leq 7.2^\circ}$ calculation formula.

Suppose the i-th measuring point with an inclination angle $\beta=144^\circ$ is $c_i$, and $p$ is the geometric center of the measuring point in the last circle, connecting point $p$ and all measuring points in the last circle to seal the model. $Op$ is the common edge of all tetrahedrons in the area. The construction of the tetrahedron in the scanning area of $\beta > 144^\circ$ is shown in Fig. 7.

![Figure 7. Construction of tetrahedron in $\beta > 144^\circ$](image)

Use $V_{c,i}$ to denote the volume of the i-th tetrahedron in the $\beta > 144^\circ$ region.

$$V_{\beta > 144^\circ} = \sum_{i=1}^{100} V_{c,i} \quad (i = 1, 2, 3 \ldots 100)$$

Total volume of goaf:

$$V = V_{\beta < 3.6^\circ} + V_{3.6^\circ < \beta \leq 7.2^\circ} + V_{\beta > 144^\circ}$$

4. Algorithm verification and application

In order to verify the reliability and accuracy of the algorithm in this paper, we conducted preliminary tests and field measurements, respectively.

In the preliminary test, a three-dimensional ranging scanning is carried out in the closed, empty room. The volume calculated by the algorithm in this paper is compared with the calculation result of 3DMine (a general three-dimensional digital mining software), and the relative error between the two is analyzed. Some comparative data are shown in Table 1.

| Measuring point number | Actual measurement volume /m³ | 3DMine calculated volume /m³ | The algorithm in this paper calculates the volume /m³ | Relative error /% |
|------------------------|-------------------------------|------------------------------|-----------------------------------------------|-------------------|
| 1                      | 138.24                        | 136                          | 135.81                                       | 0.14              |
| 2                      | 92.16                         | 91                           | 90.82                                        | 0.2               |
| 3                      | 198.72                        | 196                          | 195.81                                       | 0.09              |

Due to disorderly mining in the early years, there are a large number of unknown goafs in the Sandaozhuang mining area of Luomo Group in Henan Province. The test was carried out on a 1366-meter platform in the open-pit mining area, drilling holes on the surface of the mined-out area and performing underground three-dimensional scanning. The calculation results of some data are shown in Table 2.

| Measuring point number | 3DMine calculated volume /m³ | The algorithm in this paper calculates the volume /m³ | Relative error /% |
|------------------------|-------------------------------|-----------------------------------------------|-------------------|
| 4                      | 2955                          | 2948.85                                       | 0.21              |
| 5                      | 4821                          | 4815.49                                       | 0.12              |
| 6                      | 3223                          | 3215.64                                       | 0.22              |
| 7                      | 3852                          | 3845.21                                       | 0.18              |
| 8                      | 5466                          | 5461.12                                       | 0.09              |
The calculation results of the traditional section method and 3DMine are shown in Table 3.

| Measuring point number | 3DMine calculated volume /m³ | Section method to calculate volume /m³ | Relative error /% |
|------------------------|-------------------------------|---------------------------------------|------------------|
| 4                      | 2955                          | 2976                                  | 0.71             |
| 5                      | 4821                          | 4791                                  | 0.64             |
| 6                      | 3223                          | 3261                                  | 1.19             |
| 7                      | 3852                          | 3882                                  | 0.79             |
| 8                      | 5466                          | 5421                                  | 0.81             |

Through analyzing Table 1 and Table 2, it can be seen that the relative error between the calculation results of the algorithm in this paper and the 3DMine volume is extremely small, the relative error of the calculation in the indoor test area is within 0.2%, and the maximum relative error of the calculation of the goaf area of Luomo Group is 0.22%. The results of the two calculations are basically the same. Error analysis: 1) In the modeling process, the scattered points are directly connected. The model is equivalent to cutting corners, so it will be smaller than the actual volume; 2) Due to differences in data processing and modeling methods, the calculation results of the algorithm in this paper and 3DMine are also different.

It can be concluded from Table 3 that compared with the volume calculated by the section method, the calculation accuracy of the algorithm in this paper is significantly improved.

5. Conclusion

Based on the goaf data collected by the three-dimensional range scanner, modeling is performed, and the smallest triangular grid is constructed to construct the smallest tetrahedron with the laser emitting point as the common point. Perform coordinate transformation on all measurement points of the goaf model. The calculation is carried out in three parts, and the total volume of the mined-out area is obtained by accumulating the volume of all the smallest tetrahedrons. Through experiments and data comparison, the algorithm's reliability and accuracy have been well verified, and it can realize the volume calculation of complex internal structure space. The algorithm has a multi-loop structure, and practical applications show that it is concise and efficient.

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