Dynamic deformation and fracture characteristics of a deep roadway surrounding rock based on the machine vision monitoring method

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Abstract
The deformation and fracture of surrounding rock in deep underground engineering have the characteristics of time mutation and space continuity. In order to monitor and provide early warning of the dynamic deformation and fracture characteristics of deep surrounding rock, a real-time digital displacement measuring instrument was developed in this paper. The proposed device represented a kind of surrounding rock deformation and fracture monitoring method, which had the continuous and real-time advantages. Based upon the simulation experiments, the dynamic deformation and fracture of deep roadway surrounding rock were measured synchronously using the digital displacement measuring instrument testing system (DDMITS) and the V-STARS measurement system. Comparative measurement results indicated that the DDMITS had a higher reliability. The deformation of roadway surrounding rock gradually increased with the increase of loading. The roof deformation and caving changing patterns in coal seam mining were studied using similar simulation experiments based on the DDMITS. The vertical displacement response of rock strata was more obvious than the horizontal displacement. There was a sharp increase in the vertical displacement during the collapse of the rock strata. Additionally, the vertical displacement velocity showed fluctuations. Meanwhile, the fluctuations in the vertical displacement acceleration increased significantly. The DDMITS could achieve full-field measurement and the noncontact measurement of three-dimensional deformation.

KEYWORDS
deep surrounding rock, digital displacement, dynamic deformation and fracture, similar simulation

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INTRODUCTION

While the exploration of resources in greater geo-depths, the geological conditions are becoming complex. Meanwhile, the stability of the underground roadway surrounding rock has become of great significance.\(^1,2\) Roadway surrounding rock deformation and fracture refer to the changes in the roadway shape and size under the effect of external factors.\(^3\)\(^-\)\(^5\) Roadway deformation and destruction will block the underground traffic, increase the ventilation resistance, damage the production equipment, and eventually, result in casualties. Therefore, the monitoring and early warning of the dynamic deformation and fracture of deep surrounding rock as well as accurately mastering the status of the surrounding rock roadway stability has a certain level of significance in guaranteeing the safety of the engineering roadway during its service period.\(^6\)\(^-\)\(^8\)

For the underground engineering in deep zones, the surrounding rock deformation mainly includes two stages.\(^9\)\(^,\)\(^10\) The first stage is the initial stage of the surrounding rock deformation with elastic-plastic deformation. The second stage consists of a long period of rheological deformation. The deformation of surrounding rock shows a strong “time effect,” whereas the deformation duration is long during this stage.

When suffering the influence of complex stress in deep rock strata, the deep mining will face different engineering rock mechanical problems, which vary from shallow mining.\(^11\)\(^,\)\(^12\) The engineering rock changes its behavioral response from the shallow linear rock mechanics behavior to the deep nonlinear rock mechanics behavior.\(^13\)\(^,\)\(^14\) Furthermore, the engineering disaster caused by deep mining is increasing gradually, such as the risk of rock burst, severe mining pressure, and the acceleration of deformation of roadway surrounding.\(^15\)\(^,\)\(^16\)

The majority of the underground roadways are located in the lower intensity of the sedimentary rocks. Therefore, the stability of underground roadways is not only influenced by the underground mining, but also by the adjacent underground mining and the roadway surrounding rock dimensions.\(^17\)\(^-\)\(^19\) The deformation of surrounding rock can be divided into the surface displacement and the amount of deep displacement.\(^20\)\(^,\)\(^21\) Surrounding rock surface displacement refers to the moving distance of roadway roof, floor, or the roadsides. The existing domestic and foreign instruments used for measuring the deformation of roadway surrounding rock can be divided into mechanical measuring instruments, electrical measuring instruments, optical surveying and mapping instruments, acoustic ranging methods, laser ranging methods, optical surveying instruments, and close-range photogrammetry.\(^22\)\(^-\)\(^26\)

The mechanical measuring instruments are based on the principle of mechanical transmission. They utilize the elastic deformation caused by the force of metal components. Through amplification using the transmission system, the numerical value is displayed by means of a number of display devices. Because of the simple operation and low cost, the mechanical measuring instruments were widely used in geological engineering.\(^27\)\(^,\)\(^28\) With the development of the electromechanical integration technology, the mechanical testing instruments have realized the digital display and automatic control survey. However, in the process of deep roadway surrounding rock deformation monitoring, the process is affected by a number of factors, such as equipment installation and the cross section. Therefore, the actual accuracy of the process was not too high, and the process could only obtain the displacement from one point to the other point. Due to this drawback, the asymmetric deformation of the cross section could not be measured. The electric measuring instruments used the sensor to transform the roadway deformation into electrical signal. The instruments could be used for the measurement of cross-sectional convergence. However, the measurement accuracy was generally not high.\(^29\)\(^,\)\(^30\)

The deformation and fracture of deep roadway surrounding rock under different horizontal stress conditions were simulated and studied using the simulation experiments.\(^31\)\(^,\)\(^32\) According to a certain similarity ratio, the similar simulation tests were designed. Furthermore, the layout monitoring system, analysis of the deformation and failure characteristics of surrounding rock, as well as the support mechanism and control of the surrounding rock were also studied. The plane strain and the plane stress were used in the similar simulation experiments, which aim to study the deformation and fracture of deep roadway surrounding rock as well as the mining pressure and strata movement.\(^33\)\(^,\)\(^34\) The structural characteristics, and the deformation and failure of mining roadway surrounding rock were studied using the plane strain and stress simulation experiments.\(^35\) The plane strain similar simulations were carried out on four different types of supporting roadways. Additionally, the surrounding rock stress, the displacement, the roadway roof or floor, the displacement of the two roadsides, and the surrounding rock fracture were tested.\(^36\) The effect of the mining field on the instability of roof anchor in roadway was studied using the simulation experiments. In the experiments of similar simulations, displacement was the main monitoring index, whereas the traditional method was based on the displacement meter and contact instrument dial indicator measurement.

In recent years, the digital close-range photogrammetry techniques have been introduced to measure the deformation.\(^37\) The stereo-images of the measuring points at different time intervals were taken by the camera. The 3D coordinates of the measured points were calculated, and the displacement was obtained. The method has the advantages of noncontact measurement. However, the measurement time interval was relatively large, due to which, the data acquisition and data processing were not synchronized. The development of digital displacement measuring instruments has overcome
the deficiency of digital measurement methods. Continuous measurement and real-time monitoring of the plane displacement field can be realized. The measurement and calculation are completed automatically using a program, and the degree of automation is higher than the contemporary methods, thus overcoming the random error caused by human operation.

The dynamic deformation and fracture of deep roadway surrounding rock has the characteristics of regionality and continuity, which is due to the reason that majority roadway deformation monitoring methods are discontinuous in nature. The interval time between the two measurements is long. Furthermore, the measurement of continuity is relatively poor, and the measured value only reflects the cumulative deformation of the roadway during the measurement interval. The deformation of surrounding rock of roadway is not uniform, due to which, most of the sudden deformation information could not be measured. The existing monitoring method is single-point measurement, and the measuring points are limited. Therefore, it is difficult to achieve a wide range, multi-point measurements, and regional synchronous measurements. Due to these reasons, it is of great significance to study a kind of roadway deformation monitoring method, which has the characteristics of regionality, is continuous and provides real-time measurements.

Based on this, a real-time digital displacement measuring instrument with high precision for rock deformation was developed in this paper. The study proposes a kind of roadway deformation monitoring method, which has the characteristics of continuity and real-time. The high-precision digital displacement measuring instrument is used to study the rock deformation and failure during roadway excavation and coal seam mining. The results of the digital displacement measuring instrument and the V-STARS system were compared in the dynamic deformation and fracture of deep roadway surrounding rock. The rock deformation value, the deformation velocity, the acceleration, and some other dynamic parameters of rock mass stability and unstable critical states were analyzed.

### 2. DESIGN OF THE DDMITS

The design concept of DDMITS was to collect the video footage of the measured plane using a camera and upload it to the computer. Then, automatic identification of the tracking targets on the images was conducted, obtaining the position coordinates of the reference point. According to the calculations, the distance between the object relative to the calculated reference point was determined. The computation of the image to the object, automatic target recognition and high-precision positioning, and the image mosaic were the key contents of the DDMITS design.

For the vast majority of the camera, the image plane was always perpendicular to the axis, as shown in Figure 1. If the object plane was perpendicular to the main axis, the proportionality between the image and the object represented the ratio of the object distance and the image distance. It can be used as a solution to calculate the relationship from the image to the object. The monitoring targets need to be identified using the model image. The monitoring targets can be set not only as the local texture and gray feature of the model itself, but also as an artificial set of landmarks.

The identification point was used as a strong reflective, high contrast, highly consistent logo pattern. The measuring mark consists of a diameter of 40 mm. Two circular steel sheets with the thickness of 0.5 mm and 0.3 mm, and a special steel nail were used in this study. The steel nails riveted the 0.5 mm steel sheet, while the two steel sheets were bonded by high-strength adhesive. The artificial mark used the circular diagonal sign pattern. The second artificial mark was pasted on the steel plate. Matching measuring sign of DDMITS is shown in Figure 2.

According to the gray and geometric features of the artificial mark, the location algorithm was designed and is shown.

![Image 1](image1.png)  
**FIGURE 1** Geometric relations between the object plane and the image plane

![Image 2](image2.png)  
**FIGURE 2** The matching measure sign of the DDMITS
in Figure 2B. We used the sub-pixel positioning technology to search the vertex signs in the image and achieved the mark center positioning.

Based on the principle of machine vision, the experimental system of rock mass deformation monitoring (real-time digital displacement measuring instrument) was designed and developed. The schematic of the system and digital displacement measuring instrument is shown in Figure 3.

The DDMITS included an industrial camera, a camera frame, a camera adjustment seat, a computer, a light compensation device, a camera calibration device, artificial marking, and the DDMITS operating software. The DDMITS used four camera image stitching program, whereas the camera acquisition frequency could be adjusted. The industrial control computer was used to adjust the camera synchronization acquiring the local area gray images, which were uploaded to the terminal computer after processing. The image stitching was operated by the terminal computer and carried on the target recognition and localization. Then, the displacement field measurement was realized. The camera rack was used for fixing various cameras, adjusting the seat with axis perpendicular to the camera to ensure and guarantee equal distance. The light compensation device was used for compensating for the indoor light to avoid the camera capture too large image gray value. In order to guarantee the image mosaic, the artificial marking was used to identify the measuring point, thus facilitating the identification and location of the computer. The camera calibration device was mainly used for calibrating the camera.

The DDMITS operating software was used for the Open-CV visual algorithm and VC++6.0 program software. The DDMITS could be configured with a number of cameras and accomplish the measurement task of monocular vision and binocular vision. The DDMITS realized real-time monitoring and continuous measurement of 2D and 3D rock deformation or rock strata movement. Multiple targets could be monitored at the same time and that too within a wide monitoring range with rich measurement information.

The process of monitoring the deformation and movement of rock using the DDMITS is shown in Figure 4.

3 | SIMILARITY SIMULATION EXPERIMENTS OF ROADWAY DEFORMATION AND FAILURE BASED ON DDMITS

3.1 | Model production

The roadway prototype was a 400 m deep rock bolt support rectangular tunnel. The dimensions of the roadway section were about 3600 mm * 3000 mm. Therefore, under certain conditions, the problem of roadway deformation could be simplified as a plane strain problem. The plane strain simulation test bench is shown in Figure 5. The effective dimensions of the test bed were 600 mm (long) * 500 mm (high) * 100 mm (thick). The lifting jack loaded the stress in the vertical direction, whereas the horizontal direction was constrained by the passive plane constraint. Considering that the stress range was two times the length of the tunnel length, the dimensions of the model section were 120 mm (long) * 100 (high) mm. Furthermore, the geometric similarity ratio was \( C_l = 1:30 \). The mechanical parameters of surrounding rock were similar to the coal body, while the density of the model was 1.5 g/cm³. The density ratio was 1:0.9, and the stress ratio was 1:27.

Sand was selected as the laying aggregate model, whereas the cement material was the 425 cement and gypsum. The experimental determination of sand binder ratio was 8:1, while the water binder ratio was 1:10. Table 1 shows the concentrations of various materials used in the model. The mechanical parameters of the model are presented in Table 2. According to the measurements, the uniaxial compressive strength of H-3 ratio material was 0.45 MPa, while the internal friction angle was 39.93°. Furthermore, the cohesive force was 0.07 MPa.

The roadway support was mainly anchor support, and the similar simulation experiments used the fuse wire to simulate the anchor. The pull force experiment measured the 15 A fuse wire's tensile strength was 20 MPa. According to the stress similar ratio, the tensile strength of the anchor rod was 540 MPa, which is basically consistent with the high tensile strength.
3.2 Measurement scheme

During the roadway surrounding rock deformation similar simulation progress, due to the reason that the existing pressure sensor volume was too large (30 mm * 5 mm), the existing pressure sensor affected the overall strength and stress distribution model. Based on the above analysis, we used the polyurethane material to make the 5 mm * 5 mm * 5 mm cubic measurement block. The strain gauge was laid in the 6 cube surfaces. Through the loading experiment, the pressure measurement of the stress and deformation curve was obtained.

The strain gauge was measured using the YE2539A high-speed static strain gauge, and the stress value was calculated according to the calibration curve. The deformation of surrounding rock was measured using the DDMITS. The system works in the monocular vision visual measurement mode. The DDMITS was used to measure the plane displacement of the similar simulation experiments.

In this section, the V-STARS system was used to compare the measurement accuracy of the proposed model. In order to verify the DDMITS's feasibility, the reliability and the measurement accuracy, the DDMITS and V-STARS system were simultaneously used to measure the plane displacement in the simulation experiments. The DDMITS obtained high-resolution camera, mosaic image regions, and sub-pixel location algorithm for a variety of ways to improve the measurement accuracy. The measurement accuracy was better than 0.02 mm. The V-STARS system was developed by the American GSI company. It had the advantages of three-dimensional (3D) measurement, high precision, and fast measuring speed. Furthermore, it was currently the world's most mature commercial industrial digital photogrammetry product.

Experimental procedure: (a) According to the concentrations of various materials, the model was laid. The dimensions of the model were 2.5 m * 2 m * 0.2 m, and the measurement points were arranged on the model. The measuring point was distinguished using the circular artificial sign. Then, the vertical stress was compensated while laying the model. The support bolt and the pressure measuring module were pre-buried. (b) The model was laid down after the removal of the steel plate for 12 hours. After drying for 24 hours, plaster was cast in the model surface, and the model surface was attached to the artificial mark. (c) The experimental simulation of roadway was laid in the 400-m formation. According to the bulk density of the overlying strata, the stress value was 10 MPa. The stress ratio was 1:27, while the vertical compensation stress was 0.37 MPa. After the model was dried, the horizontal deformation constraining plywood was installed. The load of the jack was loaded vertically, while the stress was evenly and slowly loaded to a value of 0.37 MPa. The load was constant for 24 hours. (d) The roadway was mined and developed after the model stabilized. The displacement data of each measuring point were obtained with the DDMITS. The roadway was excavated, and the variations in the internal stress and deformation of surrounding rock were recorded in the process of the excavating the roadway. (e) The

FIGURE 4 Work process of digital displacement measuring system

FIGURE 5 Similar simulation plane strain test bed
load was increased. The roadway excavation and surrounding rock gradually became unstable. The vertical stress was gradually increase with the speed of 0.1 MPa/h. The surrounding rock deformation and stress changes under different loads were measured.

### 3.3 Results and discussion

1. **Deformation characteristics of roadway surrounding rock**

   The deformation process of the surrounding rock is determined from the development of the roadway to the final unstable state of the roadway as measured by the DDMITS. Figure 6A shows the images collected after the end of the roadway excavation. Figure 6B shows the coordinates of each measuring point. The measurement point of the roadway section was arranged before the roadway excavation. Figure 6C shows the comparison coordinates during each measuring point before and after the excavation.

   Under the action of active stress in the vertical direction, the displacement of the top measuring point was larger than the displacement of the bottom measuring point. From left to right, the vertical displacement of the measuring point that lied in the first lines (the third measuring point) was the largest. The measurement points of the roadside surrounding rock showed a small amount of horizontal displacement, while the displacement of the measuring point around the roadway was larger than the distance from the measurement point of the roadway.

   Figure 7 shows the displacement-time series curves of the roadway roof and floor, the roadsides displacement velocity-time curve, and the displacement acceleration time curve during the excavation to stabilize the measurement using the DDMITS.

   As can be seen from Figure 7, during the early stage of the roadway excavation, the rate of change of displacement, the acceleration speed of the roof, the floor displacement, and the acceleration speed of the roadside achieved the maximum values. Then, the values began to decline gradually. The acceleration speed reduced to negative value with the increase in time. The displacement value, the velocity, and the acceleration of the displacement tended to remain at a certain threshold value. With the increase in the time of roadway excavation, the surrounding rock gradually became stable. There was a turning point in the 24 minutes at the displacement velocity-time curve and the speed of the displacement began to slow down. The corresponding displacement-time curve and the displacement acceleration time curve also tended to plateau from this moment. This point was used as a condition to judge the stability of surrounding rock. The displacement of the roof and floor in the stable stage accounted for 7.5% of the total displacement. The instantaneous velocity of the 24 minutes accounted for 6.9% of the initial velocity, whereas the corresponding acceleration speed was within the negative range. The same analysis on the dynamic characteristic curve about the roadside was conducted. After 21 minutes, the surrounding rock tended to be stable. Corresponding to the stable phase, the displacements of the two roadsides accounted for 4.8% of the total displacement. The instantaneous velocity of 21 minutes accounted for 6.3% of the initial velocity, whereas the corresponding acceleration was within the negative range.

2. **Relationship between the overlying loading and deformation of roadway surrounding rock**

   After the initial roadway excavation to the surrounding rock stability, we continue to increase the vertical loading. The increment interval was 0.1 MPa. The loading was continuously increased until stability remained for 2 hours. Table 3 presents the deformation of surrounding rock. Figure 8 is the relationship between the vertical load-roof, and floor deformations.

   Under the same supporting conditions, with the increase of the loading, the convergence of the roadway section gradually increased. Initially, the increase of the overlying load had little influence on the deformation of the roadway. When the overlying load was up to 0.54 MPa, the influence of the loading on the roadway deformation gradually increased. When the overlying load reached 0.984 MPa, the

| **TABLE 1** Concentrations of various materials in the model |
|-----------------------------|-------------|-------------|-------------|-------------|
| Ratio number | Sand | 425 cement | Plaster | Water |
| H-3       | 8    | 0.7        | 0.3       | 0.1       |

| **TABLE 2** Results of the compression test |
|-----------------------------|-------------|-------------|-------------|-------------|
| Test number | Force direction | Specimen size Diameter | Specimen size High | Cross section The measure of area (mm²) | Destruction load (N) | Uniaxial compressive strength (MPa) |
| H-3-1 | Axial | 50.50 | 98.20 | 2002.96 | 852 | 0.43 |
| H-3-2 | Axial | 50.40 | 100.00 | 1995.04 | 659 | 0.33 |
| H-3-3 | Axial | 50.30 | 100.01 | 1987.13 | 1198 | 0.60 |
influence of the overlying load on the deformation of roadway aggravated.

Under the same supporting conditions, with the increase of the vertical load, the convergence of the section of the roadway gradually increased. The initial vertical load had little effect on the roadway deformation, as is shown in Figure 9. Meanwhile, the influence of the increase in the load on the roadway deformation gradually increased. After reaching the limit value, if the load was further increased marginally, the roadway deformation would increase dramatically. We can see the deformation and failure characteristics of roadway through the real-time images, which were mainly characterized by roof sinking and roadside convergence. The process of roadway deformation was photographed as shown in Figure 10. Figure 10A shows that when the vertical load reached 3 times of the original rock stress, local damage occurred in the roadway, and the deformation phenomenon of the roadway took place. Figure 10B shows that when the vertical load reached 6 times the original rock stress, local destruction was serious, and the failure of the roadway was obvious. The falling of the roof and the spall phenomenon were serious. The phenomenon of roof subsidence was obvious, and the convergence of roof subsidence was greater than the two sides of the roadway. Finally, the size of the roadway section changed to 104.811 mm × 93.655 mm.

4 | DEFORMATION AND CAVING OF THE ROADWAY ROOF SIMULATION EXPERIMENTS

After analyzing the deformation and failure of the roadway, the roadway roof deformation during the caving process was further studied using the simulation experiments. Based on the roof deformation characteristics, the deformation velocity, and the acceleration, the variation characteristics of roof caving were studied. Using the Chang Cun coal mine as a prototype, the dynamic deformation and fracture of deep roadway surrounding rock were measured in using the DDMITS and V-STARS measurement system simultaneously. The movement of overlying strata and the variation pattern of rock’s pressure appearance caused by the coal mining were studied.

4.1 | Model production and measurement scheme

The plane stress similar simulation test bench was selected to study the roadway roof deformation characteristics. The dimensions of the plane stress test bed were 2.5 m (long) * 0.2 m (width) * 1.4 m (high). The geometric similarity ratio of the designed model was 1:100. The similarity model was designed to move along the direction of the coal seam. The model included the coal seam and the overlying strata. The width of the model met the requirement of full exploitation of the coal face and not affected by the mining boundary. According to the Chang Cun mine borehole, comprehensive coal rock mechanics parameters and histogram model with similar material concentrations, the model was completely solidified and dried to compensate for the vertical stress.

The displacement and stress are two most important observation indices in the similar simulation experiments. The DDMITS can be used for real-time measurement of the whole-field displacement. The monocular vision

**FIGURE 6** Roadway excavation

(A) The frame after the roadway excavation

(B) Coordinate distribution of measuring points

(C) Comparison between the two frames coordinates
measurement mode was used to measure the rock deformation. In order to improve the measurement accuracy, the experimental system adopted multi-image mosaic function, circular diagonal artificial mark identification using the experimental system for displacement measuring points. The displacement meters were arranged on the back of the model. Pressure measurements were conducted using the pressure sensors. The YE2539A type high-speed static strain gauge was used to collect the data of the pressure sensors and displacement meter. The experimental instrument is shown in Figure 11.

4.2 | Results and discussion

4.2.1 | Comparison of the DDMITS and the V-STARS measuring systems

In the experiment of the plane stress model, there were some obvious regularities in the deformation of rock mass, as well as the deformation velocity and acceleration of the overlying strata failure. The roadway section established the plane coordinate system. The level of X-axis was from the right toward the positive direction of the axis, whereas the level of Y-axis was from below toward the positive direction. The roadway section and the intersection point in the ground were used as the origin of the ground. Furthermore, the X and Y direction displacements of the measuring points in the roadway section deformation during the loading are presented in Table 4.

For the V-STARS single camera three-coordinate measurement system, the measurement accuracy was 4 μm + 4 μm/m in this experiment. The measurement accuracy of this experiment was 0.008 mm. In this experiment, the measurement accuracy of the real-time monitoring system of rock deformation along the X-axis was 0.17 mm. In addition, the theoretical measurement accuracy of the axis along the Y-axis was 0.22 mm. The measurement results of

TABLE 3 Relationship between the vertical load and roadway deformation

| Vertical load/MPa | Roof and floor distance/mm | Two roadsides distance/mm | Displacement of roof and floor/mm | Displacement of two roadsides/mm |
|-----------------|---------------------------|---------------------------|----------------------------------|-------------------------------|
| 0.372           | 117.966                   | 99.195                    | 2.034                            | 0.805                         |
| 0.414           | 117.784                   | 99.007                    | 2.216                            | 0.993                         |
| 0.54            | 116.855                   | 98.568                    | 3.145                            | 1.432                         |
| 0.649           | 115.68                    | 98.185                    | 4.32                             | 1.815                         |
| 0.707           | 115.132                   | 97.579                    | 4.868                            | 2.421                         |
| 0.766           | 114.918                   | 97.259                    | 5.082                            | 2.741                         |
| 0.833           | 114.414                   | 97.037                    | 5.586                            | 2.963                         |
| 0.9             | 113.99                    | 96.728                    | 6.01                             | 3.272                         |
| 0.984           | 109.793                   | 95.186                    | 10.207                           | 4.814                         |
| 1.02            | 104.811                   | 93.655                    | 15.189                           | 6.345                         |

FIGURE 7 Deformation curves of surrounding rock

FIGURE 8 Relationship between roadway and vertical load
binocular vision real-time monitoring system were calibrated using V-STARS system, and the average values of the calculated results were as follows: $|\Delta X_1 - \Delta X_2| = 0.0329$ mm and $|\Delta Y_1 - \Delta Y_2| = 0.0289$ mm, respectively. The standard deviation was as follows: $\sigma_x = 0.0200$ mm and $\sigma_y = 0.0246$ mm. The measurement results of the two methods were in good agreement with each other, which proved that the DDMITS had high reliability.

In this experiment, the coal seam and coal pillar of 20 cm were used for the DDMITS and V-STARS8 systems, respectively, to measure the deformation characteristics during coal seam mining. Each measuring point distance was 10 cm. The point displacement was measured from 30 cm to 160 cm. Therefore, 14 groups of data were recorded separately. The DDMITS could undertake continuous measurement. The two methods were used to analyze the measured results. The vertical displacement at 70 cm of coal seam is shown in Figure 10 as the first online measure point. Figure 12A shows the digital displacement measuring instrument that measured the vertical displacement. Figure 12B shows the absolute difference between the two kinds of methods for measuring results.

Among the absolute difference results, the maximum value was 0.04 mm, whereas the minimum value was 0.01 mm. The average value was 0.021 mm, and the mean square error was 0.009 mm. After analysis of the 14-group data, the measurement result could be used to obtain the absolute difference between the DDMITS and V-STARS8 measurement systems. The maximum vertical absolute displacement difference was 0.05 mm, while the minimum difference was 0. Furthermore, the difference was 0.022 mm, and the standard deviation was 0.011 mm. The maximum difference of horizontal displacement was 0.04 mm, and the minimum difference was 0. Furthermore, the average difference was 0.019 mm, while the standard deviation was 0.008 mm.

The measurement results in the DDMITS and V-STARS8 systems were in good agreement with each other. The digital displacement measuring instrument accuracy was better than 0.02 mm, and it had high reliability. The DDMITS showed the function of automatic target recognition and high-precision positioning, multi-image mosaic, continuous measurement, real-time monitoring, automatic measurements, and other functions. The DDMITS also had more advantages than the V-STARS8 system, such as simplicity, complete measurements of the points, and the requirement of shorter time. It could also achieve real-time monitoring. Besides, the equipment input was lower than the V-STARS8 measurement system.

4.2.2 | Roof deformation and collapse characteristics

The DDMITS could automatically record the spatial coordinates of each measuring point. As shown in Figure 13, the global coordinate system was based on the upper-left corner of the model, whereas the horizontal direction was the $X$-axis and the vertical direction was the $Y$-axis.

As can be seen from Figure 11, each measuring point was surrounded by a green line segment and this area was the search area of the measuring point. According to the motion acceleration as well as the velocity and coordinates, we can...
estimate the possible coordinates of the measured points at the next moment. The search area was established by taking the coordinates as the center, so that the search range of the measuring point was reduced and the running speed of the algorithm was improved.

The displacement of each measuring point in the excavation process is shown in Figure 14.

In the vertical displacement curve of each measuring point, the vertical displacement of the left 3 points in the first measuring line was larger than that of the second measuring line. The displacement of the difference value was not too serious. This was due to the expansion of the model under the action of vertical stress. Due to the absence of lateral constraints, the overall height of the model decreased and the upper point decreased more obviously than the lower point. In the horizontal displacement of each measuring point, there appeared positive and negative values of displacements. The positive values represent the movement in the positive direction of X-axis, while the negative values represent the movement in the opposite direction of X-axis.

1. Deformation characteristics of rock strata before roof caving

Taking the fifth measuring points of the second measuring line as an example, according to the measured results, the displacement-time curve, the displacement–velocity-time curve, and the displacement acceleration time curves are shown in Figure 15.

Figure 15 shows the motion characteristics of a single point. The rock underwent collapse when the fifth measuring points of the second measuring line were at the 157 minutes. Therefore, the movement characteristics of the measuring point before 157 minutes were as follows: the vertical displacement of the measuring point increased slowly before 100 minutes and then began to show an increasing trend within the range of 100-123 minutes. The rate of the increase began to increase from 123 minutes and increased rapidly up till 156 minutes, after which, it collapsed. Before 156 minutes, the vertical cumulative displacement accounted for 5.99% of the total vertical displacement value, whereas the change of the horizontal displacement velocity of the measuring point was very small before 157 minutes. It produced horizontal displacement at it collapse. The vertical displacement velocity of the measuring point fluctuated before 123 minutes. However, all exhibited intermittent fluctuations. Additionally, the fluctuation frequency of the vertical displacement velocity was not high, and the maximum range of fluctuation was 0.45 mm/min. Fluctuation frequency increased from 123 minutes, and then, it appeared as a continuous fluctuation. The vertical displacement velocity increased rapidly from 156 minutes, and then, the roof caved. The instantaneous velocity of 156 minutes accounted for

### Table 4 Measurement results

| Measuring point | The DDMITS measurement result | V-STARS system measurement result | The absolute difference |
|-----------------|-------------------------------|-----------------------------------|------------------------|
|                 | $\Delta X_1$ | $\Delta Y_1$ | $\Delta X_2$ | $\Delta Y_2$ | $|\Delta X_1 - \Delta X_2|/\delta_{\Delta Y_1 - \Delta Y_2}$ |
| 2               | 0.8            | 0.2             | 0.791        | 0.135        | 0.009 | 0.065 |
| 3               | 1              | 0.4             | 1.016        | 0.379        | 0.016 | 0.021 |
| 4               | 0.8            | 1.4             | 0.852        | 1.474        | 0.052 | 0.074 |
| 5               | 0.2            | 3.2             | 0.160        | 3.162        | 0.04  | 0.038 |
| 6               | $-0.8$         | 1.4             | $-0.792$     | 1.377        | 0.008 | 0.023 |
| 7               | $-1.0$         | 0.4             | $-0.956$     | 0.361        | 0.044 | 0.039 |
| 8               | $-0.6$         | 0.2             | $-0.539$     | 0.110        | 0.061 | 0.09  |
8.32% of the maximum speed, while the horizontal displacement velocity fluctuation was small. The larger amplitude fluctuations appeared within the 157 minutes. The wave of vertical displacement acceleration was small before 100 minutes, and the maximum value was only 0.032 mm/min. The frequency of the acceleration fluctuation increased from 100 minutes. In particular, after 123 minutes, it continuously showed wave-like fluctuations. The range of waves was more than 0.032 mm/min. Acceleration speed was rapidly increasing in the positive range from 156 minutes, and then, the roof caved. The acceleration speed of the horizontal displacement lied within a wide range of fluctuations when the time was 157 minutes.

The same analysis of other measuring points in rock deformation to caving movement process was observed. We can obtain significant features of rock deformation through the analysis. The deformation rate and the deformation acceleration changed. These features would be used as the precursor information for rock deformation and fracture.

2. Rock strata movement and mine pressure appearance

Figure 16 shows the first caving process of the roof.

With the advancement of the working face, the rock stress shifted to the wall on both sides of the mined area. After the excavation of the working face for 32 cm, the roof caving developed rapidly and caused the first lamination of the first layer. Because of the smaller coefficient of the model material, the falling rock stratum was still a layer. With the excavation reached the depth of 50 cm, the second hierarchical of immediate roof collapses occurred. Figure 17 shows the mine pressure appearance.

After the initial collapse of the rock roof, with the working face moving forward, the direct roof collapse happened with the mining. In the face of the mining for 55 cm, the basic roof (mud stone) for the first time broke down and collapsed. The block thickness of the collapsed basic roof was about 17 cm. As the mining continued to move forward, the direct roof collapsed with the mining and the basic roof cycle collapsed. After the working face mining reached the depth of 70 cm, the cracks continued to develop. The height of the caving zone was 23.8 cm and generated 4 cm of separation.

At this point, it can be determined that the first weighing step distance of the working face was 55 cm and periodic weighing step distance was 15 cm.

5 | CONCLUSIONS

1. Based on the principle of machine vision, a new type of digital displacement measuring instrument was developed, which was used to measure the dynamic deformation and fracture of deep road way surrounding rock. The deformation patterns of roadway surrounding rock and the roof deformation and caving patterns in coal seam mining were studied using the similar simulation experiments based on the DDMITS system. The DDMITS achieved full-field three-dimensional deformation through noncontact measurements.

2. According to the comparison of the measurement results of the DDMITS and the V-STARS measurement systems, the precision of the DDMITS was better than 0.02 mm and the reliability was higher. The DDMITS achieved real-time monitoring and also had more advantages than the V-STARS measurement system, including simplicity and complete synchronous measurements of the points.

3. The deformation variations in the roadway surrounding rock according to a similar simulation experiments indicated that, from the roadway deformation to the stable process, the velocity and the acceleration of deep roadway surrounding rock reduced from the peak to a certain degree and then gradually became convergent. The deformation value of the roadway gradually stabilized after a sudden increase. The critical characteristics from the unstable condition of the roadway deformation to the steady state were obtained. The critical velocity of the roof and floor accounted for 6.9% of the initial velocity, while the velocity of the roadside accounted for 6.3% of the initial velocity. The displacement of the roof and floor accounted for 6.3% of the initial velocity. The displacement of the roof and floor accounted for 7.5% of the total displacement in the stable stage, while the roadway convergence of the roadside accounted for 4.8% of the total roadway convergence.
4. The deformation of the roadway section increased with the increase of the load under the same supporting conditions. The initial loading stage had little influence on the roadway section deformation, and the effect gradually increased.

The convergence value of the roadway section gradually increased with the increase of the vertical load under the same support conditions. The initial vertical load had little effect on the deformation of roadway, while the effect of the
increase in load on the roadway deformation gradually increased. Under the experimental conditions, the local damage occurred in the roadway when the vertical load reached three times the value of the original rock stress. When the vertical load reached six times the value of the original rock stress, the local damage changed more seriously, and the roadway deformation became more obvious.

5. The deformation value, the deformation velocity, and the deformation acceleration of the surrounding rock showed significant regularities before the overlying strata caving. The vertical displacement dynamic characteristics (displacement, velocity, and acceleration) were more obvious than the horizontal displacement. The vertical displacement rapidly increased before the roof collapsed. The vertical displacement velocity fluctuation increased continuously and the fluctuation of the vertical displacement acceleration obviously increased before the roof collapsed.

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