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Applications of a robust particle tracking velocimetry algorithm in the multiple-parametric measuring system for coal exploration industry

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Abstract. With the gradual increase in the average exploration depth of domestic coal industry, the conflict between deep coal exploration technology and exploration requirements is becoming increasingly prominent. A series of exploration disaster accidents caused by geological disasters require a high level of survey technology before the deep coal exploration. In this study, a high-resolution single hole measuring system for aquifers in coal seam is proposed. The entire system can be divided into two parts: hardware and software. The hardware probe integrates various sensors for different physical parameters using optical fibre to communicate with the controlling part above the ground. The home-made software is then used to receive and process the signals of temperature, pressure and orientation, as well as the instantaneous image sequence of aquifer with flowing contaminants. A home-made novel particle tracking velocimetry algorithm based on Voronoi diagram is used as the core algorithm to analyse the image sequence and obtain the magnitude and direction of flow at the measuring spot of aquifer. After practical tests, the system is confirmed to be able to effectively monitor the hydrological conditions of the aquifer in coal seam. Therefore, the proposed algorithm can be applied to the evaluation of hydrogeological conditions before well establishment for coal-exploration and to the prevention of potential dangers during the exploration work.

The precise exploration of hydrogeological conditions in coal explorations plays an important role in determining the safe coal production [1,2]. Effective monitoring methods are the fundamental solutions to avoid exploration disasters and accidents. Traditional methods for measuring the velocity and flow direction of aquifer are indirect; empirical formulas are used to calculate the aquifer velocity, which cannot ensure the accuracy of the measurement [3]. With the development of electronic technology, the direct measurement of seepage in aquifers through integrated single hole equipment has been widely studied and applied [4,5]. The velocity and flow direction of aquifers and other hydrogeological parameters are tested by the following methods. Firstly, aquifers are marked with radioisotope tracers, and the aquifer flow velocity and direction are determined through the tracer method. Secondly, the natural potential and charging methods in hydro-geophysical prospecting are adopted. Thirdly, the flow velocity and direction are measured using the thermo sensitivity method. However, the abovementioned methods pose disadvantages in the long-term field application: (1) the methods have low sensitivity in terms of detection of aquifer flow velocity and direction; (2) there is a gap (or a tuning coefficient that is local and thusly difficult to determine) between the indirect observation result and the real flow field. Hence, this study proposes a high-resolution system for directly measuring the flow velocity and direction and other hydrogeological parameters of aquifers in coal seam. This system is dedicated to a full reflection of the hydrogeological information of aquifers in coal seam, and to improve the reliability of the exploration of hydrogeological conditions and reduce the prediction error of water inflow in explorations. This system is expected to provide technical support for the improvement of water resource monitoring and water environment protection in mining areas.

1. Core algorithm

The traditional single hole measuring system for flow velocity and direction of aquifer is equipped with isotope tracer. Radioisotopes are used to mark the aquifer: the concentration in the tracer continuously decreases with the dilution of water flow, so the velocity of the borehole can be obtained by recording the change of isotope concentration [6,7]. However, if radioisotopes are used as tracer, protective measures should be applied to prevent any possible contamination during the operation. This process is generally difficult for technicians. Aquifer contains micron-sized sand and gravel particles; if the flow viscosity is higher than that of air, the carrying capacity of fluid is large. Therefore, sand and gravel particles can be used as natural tracer particles for water flow. High-speed digital photography and particle tracking velocimetry (PTV) are used to perform the cross-frame matching (tracking) of suspended particles in aquifer to obtain the velocity in the “forward difference format” on the feature plane. The operation is simple, has no interference and exhibits high measurement accuracy. Moreover, the measurement errors are mainly concentrated in the recognition process of the particle centre (about 0.1 pixels). Therefore, a self-made particle tracking algorithm is developed to process the image sequence of the flow field to obtain the flow characteristics of aquifer.

PTV algorithms have been continuously developing as a means of reconstructing particle trajectories in a flow field. Amongst the algorithms, the particle cluster algorithm is the easiest to operate because it delivers the quickest updates by considering two- and three-dimensional versions with few pre-setting parameters [8,9]. Classical particle cluster PTV algorithms include spring model based PTV and velocity gradient tensor PTV [10,11]. However, both algorithms demonstrate difficulty in defining the size of the particle cluster. In particle matching, the size of a particle cluster will change with the size of particle displacement. This problem can be avoided by using appropriate meshing techniques. In addition, the result obtained for a single image using the same partitioning algorithm is unique, thus overcoming the uncertainty in the size of the particle cluster. Song et al. connected the discrete particle points in an image to nonoverlapping triangles using the Delaunay Tessellation (DT) technique. Then, they conducted double-layer matching for the triangle and the vertex of the triangles in the two consecutive frames to obtain the matching results of particles [12]. This algorithm is referred to as the DT-PTV algorithm. However, triangles are simple and have few characteristics; thus, triangles become intrinsically “the same” when the particle density is high. As a result, the accuracy of the algorithm is limited [13,14]. To overcome the high self-similarity of triangles, the present authors developed a cytochemical treatment of discrete points using the Voronoi Diagram (VD). In this study, this new PTV algorithm is adopted to postprocess the images and obtain the flow velocity and direction of contaminants in aquifer.

The aquifer image collected by the camera is initially background-erased using matrix subtraction in a “central difference format”. Then, the Gaussian filtering function is adopted to denoise the images. The reconstructed image is shown in Figure 1(a). The coordinates of the identified particle domain centres are used as the input parameters for PTV, as shown in Figure 1(b). After obtaining the coordinates of the particle centre in image, the image is divided into polygonal cells with different sizes and shapes using the VD grid generation technology. In other words, after VD division, the planar regions with several discrete points are divided into nonoverlapping polygons, which are called Voronoi cells, as shown in Figure 1(c) and Figure 1(d). The above VD division is applied to the two consecutive images.

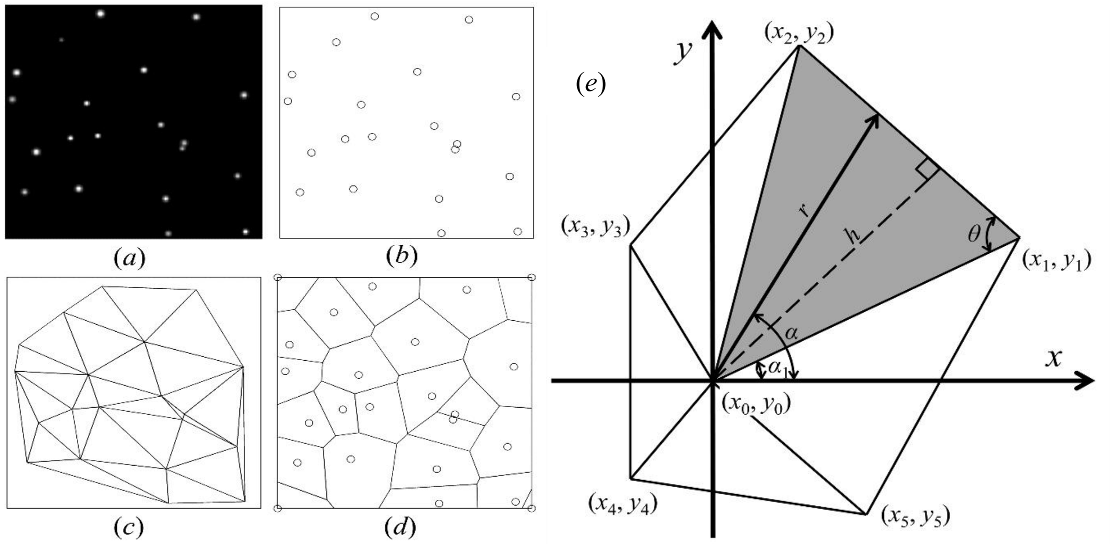

Figure 1. PTV processing: (a) Particle image generated after background removal and denoising; (b) Identification of particles from the images; (c) Triangular grid from DT; (d) Cell arrays obtained by DT transposing VD. (e) Calculation of the characteristic curve of a cell comprising vertices (x_i, y_i) (i = 1~5).

Based on the hypothesis of limited deformation in continuous flow, the corresponding cells of the same particle will not undergo large deformation across the frames. Therefore, the new PTV can be utilised to obtain the matching result of the two frames of particles by determining that of the two frames of cells. Firstly, the characteristic curve of a single cell is extracted. The radius from the particle point to the outer edge of the cell is used as the characteristic curve of the cell. The calculation formula for the characteristic curve $\boldsymbol{r}$ is shown in equation (1), where the parameters are shown in Figure 1(e).

$$\boldsymbol{r}(\boldsymbol{\alpha}) = \frac{h}{|\sin(\boldsymbol{\alpha}+\theta_1-\alpha_1)+1-\mathrm{logical}(\theta_1-90^\circ)|} \quad \mathrm{logical}(x) = \begin{cases} 1 & (x \neq 0) \\ 0 & (x = 0) \end{cases},$$
$$h = \frac{|Ax_0+By_0+C|}{\left(A^2+B^2\right)^{1/2}} \quad \begin{cases} A = y_2 - y_1 \\ B = x_1 - x_2 \\ C = x_2 y_1 - x_1 y_2 \end{cases} \tag{1}$$

Secondly, to compare a pair of characteristic curves ($\boldsymbol{r_1}$ and $\boldsymbol{r_2}$) from two respective frames, both are nondimensionalised by dividing each by $(|\boldsymbol{r_1}|^2+|\boldsymbol{r_2}|^2)^{1/2}$ to avoid the effect of cell size on matching results. The covariance of the two curves is calculated using equation (2). The particles with the smallest cell-to-cell difference are considered as matching particles.

$$C_r = \frac{\mathrm{cov}(\boldsymbol{r}_1, \boldsymbol{r}_2)}{\left[\mathrm{cov}(\boldsymbol{r}_1, \boldsymbol{r}_2)\right]^{1/2}} \tag{2}$$

The matching results can only be considered effective if the corresponding cells are sufficiently similar. Therefore, a judgment must be added to the matching result. If the covariances between the cell corresponding to a particle and any of the cells of all candidate particles are less than 0.5, the particle does not match in the second frame. In applications, 0.5 corresponds to the median value between two cases in which the cell is completely different and completely identical, respectively. For the flow with strong deformation, the judgement is suggested to between 0.25 and 0.5.

Based on the new PTV, the cells obtained from the Voronoi partitions are used to perform particle matching. The individual difference of cells is much larger than that of triangles. The triangular convergence like DT-PTV will not occur when the density is high. Therefore, the new PTV performs well when the particle concentration and local distortion of the flow field are large, which is consistent with the wide operating conditions of aquifer flow. In addition, this algorithm has simple structure and high computational efficiency. With only one pre-setting parameter, the robustness is high after realising the soft– and hardware connection. This new algorithm is integrated into the Aquifer Monitoring Program V1.0 to achieve the real-time calculation of aquifer flow information.

2. Hardware

The proposed high-resolution single hole measuring system for aquifers in coal seam consists of a probe, a signal processing module and a computer terminal. The probe will go deep underground to collect the hydrological characteristics of aquifer. The signal processing module and personal computer terminal are used for data processing. The probe and the ground are connected by optical fibres for signal transmission shown in Figure 2. The probe is used to collect the temperature and pressure of aquifer and flow field images. The new PTV algorithm is adopted to process the image sequence of the flow field. Then, based on the absolute geographic direction collected by the compass, the flow velocity and direction of aquifer is finally obtained.

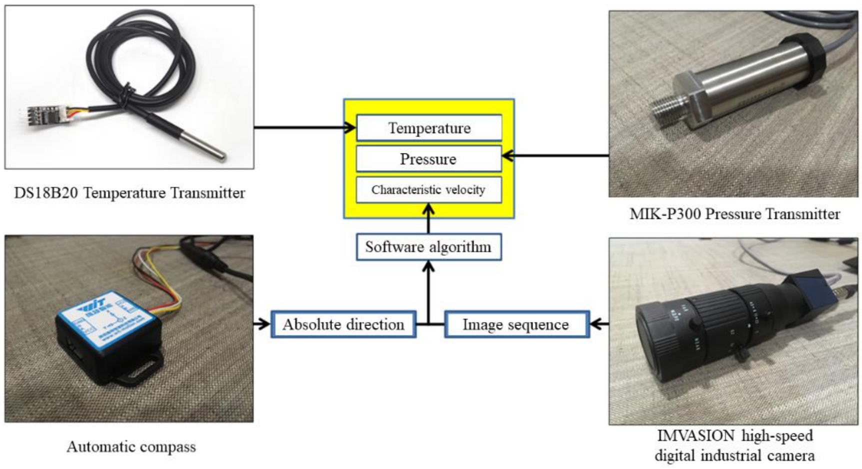

Figure 2. Constitution of the single hole measuring system for aquifer flow.

The sensor, camera and wiring are protected by encapsulating the probe part in a stainless and steel cylinder with a length of 700 mm and a diameter of 65 mm. The cylinder consists of two parts: top and bottom. The two parts are connected by welding three steel tubes arranged in a regular triangle to save framing space. The lower cylinder is responsible for collecting the temperature and pressure information of aquifer. A DS18B20 temperature sensor module and an MIK-P300 pressure transmitter are encapsulated, which is installed behind the water hole. DS18B20 is a commonly used digital temperature sensor that outputs digital signals. The temperature measurement range is from −55°C to 125°C. The inherent temperature measurement error is ±1°C between −10°C and 85°C. The measurement error is ±0.5°C. The range of MIK-P300 pressure transmitter is 0–2 MPa, and the measurement accuracy is 0.1% FS. A silicon piezoresistive pressure oil-filling core served as the pressure sensitive core. The integrated circuit converts the millivolt signal of the transducer into a standard voltage signal. All signals are transmitted along their respective lines to the integrated chip inside the upper cylinder. The holes on top of the lower cylinder are used to install lighting components for framing. The longer cylinder on the upper side collects aquifer images and monitors the status of the probe. An IMVASION high-speed industrial digital camera and lens are installed at the lower hole, whereas the digital posture sensor compass and camera-sensor integrated chip for data reception and transcoding are installed on top. The maximum framing frequency can be set as high as 50 Hz. The measuring range of the electronic compass is ±180° and the measuring error in static rate is ±0.05°. In all, one can tell that the entire system possesses good temporal resolution in acquiring data.

The collected data are transmitted by optical fibre to ensure the quality and efficiency of communication. The image data collected by the camera and the signal collected by the sensor are transmitted by two independent optical fibres to avoid mutual interference. Optical fibers are integrated with the power lines of each component, and the signal processing module reaches the surface through the wiring holes. The signal processing module is composed of corresponding signal converters, which convert optical signals into digital signals that can be recognised by a computer. Data are eventually transmitted to the personal computer terminal for further processing. The whole system is powered by a 220V AC power.

3. System calibration

All parts should be calibrated before using the overall measuring system. The temperature and pressure sensors and electronic compass adopt the integrated sensor module; thus, additional calibration is not required. However, the flow information collected by the camera only depends on the reference system where the camera is located; hence, the velocity and direction must be calibrated before use. The particle velocity obtained by the algorithm should be multiplied by the object-to-distance ratio of the camera to obtain the actual size. The object-to-distance ratio can be determined by capturing a photo of a reference object with known length. The actual direction can be obtained by jointly processing the velocity direction with the direction information collected by the electronic compass.

As for the calibration of the flow direction angle, considering that the camera and compass are installed on transition plates parallel to each other by threads in the probe, the photographic plane of the camera is parallel to the horizontal plane of the compass. Therefore, only the correction of horizontal angle should be considered. For the velocity direction angle, when the fluid is required to move to the east, the velocity direction angle is 0°. The anti-clockwise direction is set as the positive orientation. For example, when the velocity direction angle is 90°, the fluid moves northward.

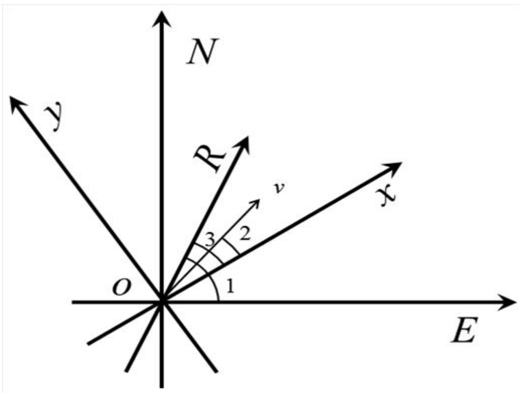

Figure 3. Angle calibration diagram for flow direction.

In Figure 3, *R* refers to the compass direction axle, the *EoN* coordinate system represents a geographic coordinate system, *N* refers to the due north, *E* refers to the due east, and the *xoy* coordinate system represents the photograph coordinate taken by a camera. The geographic coordinate system moves based on the earth's movement. No rotation is observed. The camera and electronic compass are installed in the probe, and no relative movement with the probe is set. The *xoy* coordinate system and *R* can freely rotate around point *o*. However, the angle $\angle 3$ between *R* and *x* does not change in the rotation. $\angle 3$ is also the target angle in the angle calibration. In addition, due to the problems on computer image data storage, the picture coordinate system is usually a left-handed coordinate system. Backward processing for the *y*-axis is therefore necessary. The angle between the movement velocity *v* and the *x*-axis is $\angle 2$, which is obtained through PTV. $\angle 1$ refers to the angle between the geographic coordinate system and *R*. The output of the compass in the horizontal level is recorded. Figure 3 shows that the actual direction of the particle velocity $\angle v$ is shown in equation (3):

$$\angle v = \angle 1 - \angle 3 + \angle 2 \tag{3}$$

Where ∠1 refers to the read value of the angular sensor in the horizontal level, ∠2 can be calculated through particle tracking algorithm, and ∠3 is the angle waiting for calibration. Ensuring that the geographic coordinate system overlaps with the image coordinate system is necessary. The horizontal angle reading output from the angle sensor is ∠3 after inputting this angle in the calibration parameters of the software. This phenomenon indicates the completion of the systems angle calibration. After encapsulation and calibration, the whole probe is lowered to a predrilled hole for 3 min before the official test.

4. Software interface

A self-developed software called Aquifer Monitoring Program V1.0 is used to control the self-designed measurement system. The self-developed software adopts the Qt application development framework. Qt supports numerous operating systems and has strong cross-platform capabilities. This framework can run on mainstream platforms, such as Windows, Linux, Android and IOS. The developed software has good performance due to the close combination with C++, which is close to the performance of that developed by Native. Moreover, the Qt development framework contains various mature class libraries with abundant functions. The Qt framework supports open graphic library (OpenCV) and provides great convenience for graphic processing in this research. OpenCV is an open-source cross-platform computer vision library that contains numerous general algorithms for image processing and computer vision [15]. Meanwhile, these platforms are written in C++ language, which reduces the difficulty of any further maintenance.

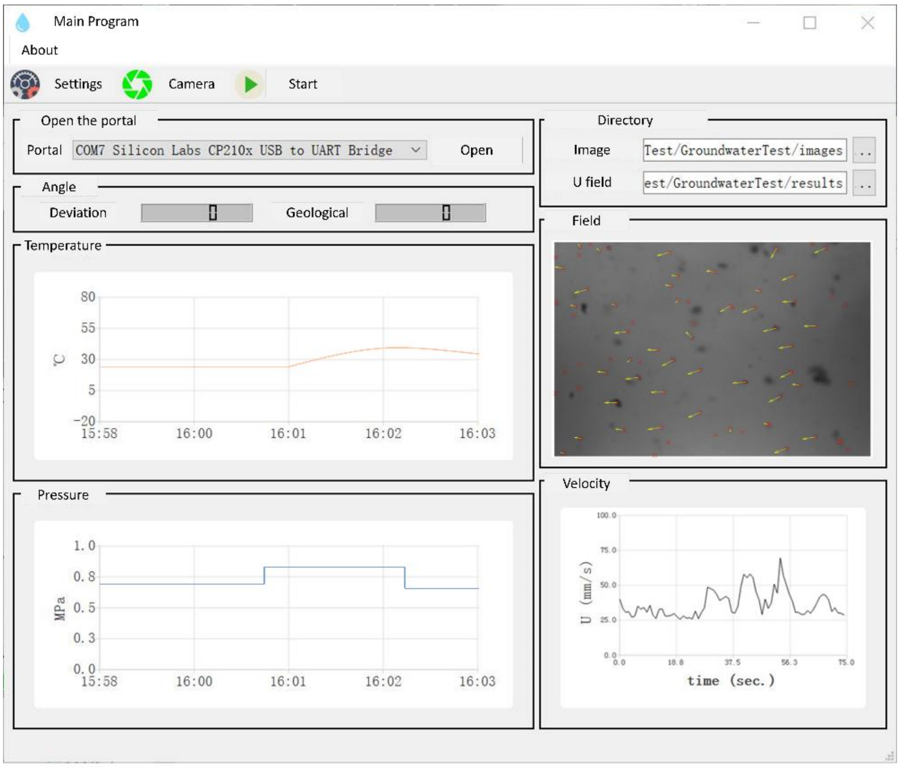

Figure 4. Software interface of Aquifer Monitoring Program V1.0.

As shown in Figure 4, camera-related parameters can be controlled by the parameter configuration algorithm in the upper left corner of the software interface, such as the radius of PTV interrogation domain and the camera framing frequency. On the left side of the main interface, the software reads the real-time temperature and pressure data, as well as the data from the posture sensors through the question-and-answer mode for the combined serial port. The default framing frequency is set as 10 Hz. Data related to temperature and pressure are displayed on the screen in real time. Data from the posture sensor will be combined with particle velocity to display the real-time mainstream geographic orientation and the elevation of the probe relative to the horizontal plane. When the camera is switched on after configuring all the parameters, sampling can be initiated by choosing the directories of image backup and PTV result storage on the right side of the main interface. The image sequence will be saved in the local hard drive for later viewing. The PTV algorithm module is then used to process the image sequence and obtain real-time aquifer flow velocity and direction. In addition, the variation of characteristic velocity (spatial-averaged) with time in the flow field is shown in the lower right corner. After the calculation is completed at the end of sampling, the software will generate hydrological reports based on the collected data and compress the flow field images to save storage space. The flow field of aquifer obtained from PTV matching is shown in the upper right corner. The large and stationary stains in the background are successfully removed. The cross marker is the coordinate of the identified particle points, and the arrows refer to the velocity vector of particles. After placing the probe in the position, the measured characteristic velocity appeared continuous, which is consistent with the actual flow condition of aquifers. In other words, we found that the flow fields across the two consecutive frames are relevant to each other, and no velocity abnormality is observed during the monitoring. Therefore, the present system works effectively in measuring a classical aquifer in coal seam.

5. Conclusion

Around a homemade PTV algorithm, a high-resolution single hole measuring system for the flow of aquifers in coal seam has been established. Owing to the simple structure (good efficiency) and reliable principles (satisfactory accuracy) of PTV algorithm, the system has been demonstrated to be effectively measuring the hydrological condition of the aquifers in coal seam. The collected data can serve as a reliable reference in evaluating the influence of aquifer on the production of coal industry.

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References

[1] Zhang X D, Liu X R 2011 A study on the feature and formation mechanism of super karst water burst in deep karst tunnel *Industrial Construction* **41** (4): 79

[2] Zhang L H, Wang S D, Tang Z G, Wu H J, Duan X and Peng S Y 2008 The harm of water to high way and influence of high way on water environment *J. Catastrophology* **23** (1): 76-77

[3] Wang Y J 2006 Hydrogeological exploration method for measuring aquifer flow velocity and its effect *West-china Exploration Engineering* (3): 124-125

[4] Mu Y Q 2007 Technical analysis of single hole steady flow pumping test *Heilongjiang Science and Technology of Water Conservancy* (6): 50

[5] Gu S Q and Song Jisu 2010 Discussion on the test method and quality requirements of deep hole field pumping *Energy Technology and Management* (2): 73-74

[6] Zhao X H, Wang Y M, Pan G F and LI Y J 2011 Development of aquifer flow rate measurement system based on isotope logging technology *Science & Technology Information* (10): 783-784

[7] Lu C P, Shu L C, Yuan L B, Zhang R R, Huang B J and Wang B B 2009 Determination of hydrogeologic parameters of karst auifer based on tracer test *J. Jilin University (Earth Science Edition)* **39** (4): 717-719

[8] Cui Y T, Zhang Y, Jia P, Wang Y, Huang J C, Cui J L and Lai W T 2018 Three-dimensional particle tracking velocimetry algorithm based on tetrahedron vote *Experiments in Fluids* **59** (2): 31

[9] Zhang Y, Wang Y and Jia P 2014 Improving the Delaunay tessellation particle tracking algorithm in the three-dimensional field *Measurement* (49): 1-14

[10] Okamoto K, Hassan Y A and Schmidl W D 1995 New tracking algorithm for particle image velocimetry *Experiments in Fluids* **19** (5): 342-347

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[11] Ishikawa M, Murai Y, Wada A, Iguchi M, Okamoto K and Yamamoto F 2000 A novel algorithm for particle tracking velocimetry using the velocity gradient tensor *Experiments in Fluids* (29): 519-531
[12] Song X, Yamamoto F, Iguchi M and Murai Y 1999 New tracking algorithm of PIV and removal of spurious vectors using Delaunay tessellation *Experiments in Fluids* (26): 371-380
[13] Zhang Y, Wang Y and Jia P 2015 A particle tracking velocimetry algorithm based on the Voronoi diagram *Measurement Science and Technology* (7): 075302
[14] Jia P, Wang Y and Zhang Y 2013 Improvement in the independence of relaxation method-based particle tracking velocimetry *Measurement Science and Technology* (24): 055301
[15] Xi Y D, Zhang Y S, Yu Y and Tang Z H 2018 Design of Low Slow Small Target Tracking System Software Based on OpenCV *Industrial Control Computer* **31** (07): 103-104