Journal of Image Processing Theory and Applications (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jipta.2024.070107
ISSN 2560-6239 Vol. 7 Num. 1

Research on High Speed Particle Tracking Measurement Method Based on Ultra High Speed Pulse Camera

Shenghong Fan, Wenjie Fan, Jie Ren, Pan Li

Beijing Prodetec Technology Co. Ltd., Beijing, 100083, China

Keywords: High Speed Particle, Tracking Measurement, Image Processing, Spatial Positioning Accuracy, Pulse Camera

Abstract: This article studies the high-speed particle tracking measurement method, aiming to simulate the tracking measurement of high-speed particles by monitoring the splashed debris in the sample container, and measuring the motion speed, motion angle, and sputtering trajectory of the gravel particles. The system consists of 5 ultra high speed pulse cameras, which collect particle images and perform differential and threshold segmentation methods on the images to achieve particle recognition and localization. The particle motion speed is calculated by estimating the particle's position changes between different frames. The experimental results show that the system can achieve tracking of high-speed moving particles, with a spatial positioning accuracy of ± 0.2mm and a measurement error of 10%. This method provides certain theoretical and data support for the tracking and measurement research of high-speed particles.

1. Introduction

With the development of scientific research, accurate tracking of high-speed particle motion is a key requirement for fields such as particle physics and fluid mechanics [1]. However, traditional camera technology often struggles to meet this demand under high-speed conditions. The emergence of ultra high speed pulse cameras has brought new possibilities to solve this problem. The basic principle of an ultra high speed pulse camera is to independently work on each pixel, continuously and completely record the changes in light, and can continuously restore and present clear images at any time [2]. This technology mainly draws on the biological principle of neural pulses generated by photoreceptor cells in the retina of primates when stimulated by light. Specifically, it modulates the photoelectron flow into a digital pulse sequence, achieving digital expression of the photocurrent process [3]. In an ultra high speed pulse camera, each pixel accumulates charge from the clear state and automatically resets and restarts accumulation when the pressure difference reaches a specified threshold. At the same time, it will generate a pulse as the accumulation mark, and the pulse width of this pulse represents the time experienced by accumulation. All pulse sequences generated by pixels are arranged in pixel space to form a pulse sequence display, thereby achieving digital expression of incident optical flow on the image plane [4].

Theoretical analysis shows that ultra high speed pulse cameras can approach or even approach the physical limits of optoelectronic devices. Unlike traditional exposure devices, it does not require an exposure process and can achieve ultra-high dynamic range, ultra-high speed, and continuous imaging without blurring [5]. This makes ultra high speed pulse cameras an ideal choice to meet the accurate tracking needs of high-speed particle motion. Ultra high speed pulse cameras are mainly used in professional fields such as scientific research, engineering testing, and high-speed dynamic analysis. It can capture details of high-speed motion, transient events, or rapid reactions, and is used to study the motion, deformation, collision, etc. of objects. Traditional cameras are widely used in fields such as daily photography, video shooting, and security monitoring.

Ultra high speed pulse camera is a high-speed, high dynamic continuous imaging camera developed based on the principle of pulse continuous imaging. It has a leading advantage in solving the pain points of "ultra high speed, high real-time, and intelligence" in high-end applications in the visual industry.

Particle fields are widely present in scientific research, production, and daily life. The measurement of high-speed particles mainly includes transient scattering technology [6], transient holography technology [7], laser Doppler velocimetry technology [8], Particle Image Velocimetry (PIV), high-speed photography technology [9], and meter scattering imaging technology. In recent years, significant progress has been made in the research of ultra high speed pulse cameras [10-15]. Among them, Professor Huang Tiejun's team from Peking University proposed an innovative visual model - the pulse vision model, and successfully developed a pulse vision chip [16]. This technology enables high-speed pulse cameras to achieve clear visual imaging, and they have also successfully manufactured a million pixel pulse vision camera with a sampling frequency of up to 40000 Hz. In terms of application, the team demonstrated the real-time tracking ability of the camera in high-speed rail detection. By detecting high-speed trains traveling at a speed of 700km/h (0.5 Mach) within a distance of 2 meters, this camera can not only clearly distinguish air shock waves, but also record and detect the changes in shock waves generated during high-speed movement in real time. In addition, the camera has demonstrated long-term real-time observation capabilities for the Mach 6 wind tunnel in scientific research observations [17].

Overall, research and experimentation on high-speed particle tracking measurement methods for ultra high speed pulse cameras are still in their early stages. This article proposes a comprehensive measurement method that combines computer vision and image processing technology, and conducts relevant experiments. This study provides theoretical and technical support for the research of tracking measurement methods for high-speed particles in ultra high speed pulse cameras.

2. Principle of Particle Tracking Measurement with 2 Ultra High Speed Pulse Cameras

This article adopts the method of multi camera photogrammetry to track and measure high-speed particles. Multiple ultra high speed pulse cameras are arranged at different angles to collect information on high-speed particles. Then, threshold segmentation is used to recognize the particles and obtain their precise three-dimensional spatial positions. Finally, the trajectory of the particles is measured and fitted to complete the tracking of high-speed particles.

2.1 Ultra high speed pulse camera imaging

Traditional film imaging is a photochemical reaction process that can only be achieved through timed exposure. CMOS photoelectric sensors (the relevant principles and methods are also applicable to other photoelectric sensors) use photodiodes to convert photons into photo generated carriers carrying charges. Each pixel is independent and does not require synchronous exposure like film imaging. Instead, they can convert the received photon stream into an electron stream separately. By continuously measuring photocurrent and converting it into digital information flow, continuous expression is achieved. All pixels are arranged in an array according to spatial relationships, and the digital stream output by each pixel is a continuous expression of the light process shining on the plane of the pixel array, from which an image at any time can be obtained. The principle course on ultra high speed pulse camera imaging is based on the relevant paper of Professor Huang Tiejun from Peking University [17].

2.2 Multi camera calibration

Multi device calibration is based on spatial resection, using several ground control points and their image points on the image to determine the external orientation elements of the image.

The spatial resection of a single image is the process of calculating the internal and external orientation elements of the image based on a certain number of control points (points with known coordinates) and their corresponding image points using a mathematical relationship. When measuring with a single camera, the measuring rod coordinate system is used as the auxiliary control coordinate system, and the marker points on the measuring rod are used as the auxiliary control points. The collinear equation is listed to solve the external orientation elements of the image in the measuring rod coordinate system($X_S,Y_S,Z_S,\omega,\varphi,\kappa$). Six collinear equations can be listed for the three marked points on the measuring rod:

$$\left.\begin{aligned} x_i - x_0 + \Delta x &= f\frac{a_1(X'_i - X_S) + b_1(Y'_i - Y_S) + c_1(Z'_i - Z_S)}{a_3(X'_i - X_S) + b_3(Y'_i - Y_S) + c_3(Z'_i - Z_S)} \\ y_i - y_0 + \Delta y &= f\frac{a_2(X'_i - X_S) + b_2(Y'_i - Y_S) + c_2(Z'_i - Z_S)}{a_3(X'_i - X_S) + b_3(Y'_i - Y_S) + c_3(Z'_i - Z_S)} \end{aligned}\right\} \tag{1}$$

In the above equation: i=1,2,3;X_S,Y_S,Z_S,a_i、b_i and c_i(i=1,2,3) are the translation amounts of the external orientation elements of the image and the elements of the rotation matrix; X0, y0, f, Δ x, and Δ y are the internal parameters of the image, which have been pre calibrated and can be considered as known values.

Considering that the coordinates of the control points and the values of the internal orientation elements are known, the form of the error equation in equation (2-1) is:

$$V = C\Delta + L \tag{2}$$

Where,

$$V = \begin{bmatrix} v_{xi} & v_{yi} \end{bmatrix}^T$$

$$C = \begin{bmatrix} \frac{\partial x_i}{\partial X_S} & \frac{\partial x_i}{\partial Y_S} & \frac{\partial x_i}{\partial Z_S} & \frac{\partial x_i}{\partial \omega} & \frac{\partial x_i}{\partial \varphi} & \frac{\partial x_i}{\partial \kappa} \\ \frac{\partial y_i}{\partial X_S} & \frac{\partial y_i}{\partial Y_S} & \frac{\partial y_i}{\partial Z_S} & \frac{\partial y_i}{\partial \omega} & \frac{\partial y_i}{\partial \varphi} & \frac{\partial y_i}{\partial \kappa} \end{bmatrix}$$

$$\Delta = \begin{bmatrix} \Delta X_S & \Delta Y_S & \Delta Z_S & \Delta\omega & \Delta\varphi & \Delta\kappa \end{bmatrix}^T$$

$$L = \begin{bmatrix} x^0{}_i - x_i & y^0{}_i - y_i \end{bmatrix}^T$$

In the error equation (2-2), the number of unknowns is 6. Therefore, only 3 landmark points are needed to list 6 equations to solve. For measuring rods with more than 3 marker points, if the number of equations is greater than the number of unknowns, the least squares adjustment can be used to solve.

2.3 Particle recognition

In this scheme, the research adopts a frame difference method before and after to achieve target recognition and positioning. Image comparison is an image processing method that aligns two or more images obtained from the same sensor at different times and under the same imaging conditions on the same scene in space and identifies differences.

Some of the steps are as follows:

1) Image subtraction: The process of subtracting pixels from two input images at the same position to obtain an output image. Assuming two input images are f1 (x, y) , f2 (x, y), The two images have the same size and number of channels, and the output image is g (x), y), The image subtraction formula is as follows:

$$g(x,y) = f1(x,y) - f2(x,y)\#(2-3) \quad (3)$$

2) Image filtering: It refers to the suppression of noise in the target image while preserving the detailed features of the image as much as possible. Common filtering methods include spatial filtering and frequency domain filtering. The Gaussian filter is used in this article. Gaussian filtering is a type of linear smoothing filter that selects weights based on the shape of the Gaussian function. Simply put, Gaussian filtering is the process of weighting and averaging the entire image. The value of each pixel is obtained by weighting and averaging its own and other pixel values in the neighborhood. The specific operation of Gaussian filtering is to use a template (also known as convolution or mask) to scan each pixel in the image, and replace the value of the central pixel in the template with the weighted average grayscale value of the neighboring pixels determined by the template.

3) Threshold segmentation: It is the combination of two types of regions (target and background) with different grayscale levels in an image, utilizing the differences in grayscale characteristics between the target to be extracted and its background. Select an appropriate threshold to determine whether each pixel in the image should belong to the target or background area, thereby generating the corresponding binary image. The basic process of threshold segmentation is to first determine the threshold, then compare all pixel values in the image with the threshold, and divide the pixels into two categories based on the comparison results: target or background.

4) Connected Component generally refers to the image region composed of foreground pixels with the same pixel value and adjacent positions in the image, Blob)。Connected Component Analysis, Connected Component Labeling refers to identifying and labeling various connected regions in an image.

After the above steps, a particle distribution diagram can be obtained as shown in the following figure 1:

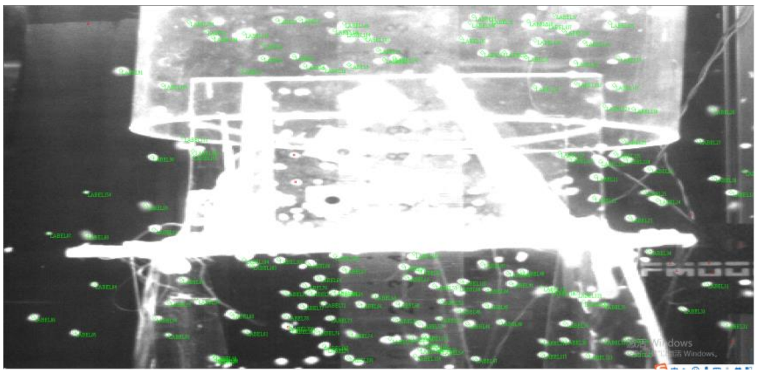

Figure 1: Schematic Diagram of Particle Extraction

2.4 Particle coordinate calculation

After obtaining the photo data of the test object, the camera also becomes an independent coordinate system based on the known external orientation elements($X_S, Y_S, Z_S, \omega, \varphi, \kappa$) between the binocular vision systems. The relationship between the camera coordinate system and the photogrammetric coordinate system has been established, that is, the independent coordinate system $O' - X'Y'Z'$, first shifts (X_S, Y_S, Z_S), and then rotates ω、φ and κ around the X 'axis, Y' axis, and Z 'axis in order to coincide with the photogrammetric coordinate system *S-XYZ*.

The coordinates of the particle center target P in an independent coordinate system are (X', Y', Z'). If its coordinates in the photogrammetric coordinate system are (X, Y, Z), then:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \begin{bmatrix} X' - X_S \\ Y' - Y_S \\ Z' - Z_S \end{bmatrix} \tag{4}$$

Based on the known external orientation elements in the image, the principle of kernel line matching is used to match other non landmark points with the same name, and the beam method adjustment is used for calculation. The beam method adjustment model refers to the calculation of external orientation elements and model point coordinates in analytical photogrammetry, which is carried out as a whole, and is called the beam method. Beam adjustment is a mathematical model based on collinear equations, where the observed values of the image plane coordinates of an image point are nonlinear functions of unknown variables. After linearization, they are calculated according to the principle of least squares. This calculation is also based on providing an approximate solution and iterating step by step to reach the optimal value.

2.5 Particle trajectory measurement

After multiple cameras form a binocular and jointly build a station, measurement work can be achieved. By collecting data and images of high-speed particles, three-dimensional point coordinate data of several particle positions can be obtained. The continuity of these three-dimensional point data becomes the particle's motion trajectory. The recognition and tracking of this particle require time calculation to obtain continuous tracking of a target.

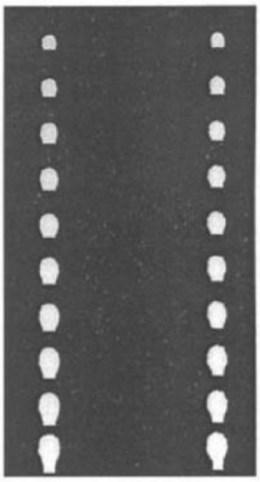

Figure 2: Particle Trajectory Diagram

For two-dimensional particle images, by obtaining the centroid coordinates of particles, the dynamic motion process of particles can be obtained, and the displacement size of particles can be obtained. Based on the exposure time of the camera, the growth rate and rise rate of particles can be calculated. Due to the close symmetry and uniform quality of particle images (each pixel has the same grayscale value, i.e. the same density), using the centroid method can conveniently, quickly, and accurately obtain the centroid coordinates of particles composed of bright spot coordinates (because the centroid coincides with the centroid).

By performing image preprocessing and image analysis on a sequence of captured particle images, a complete image of the filled particles is obtained, as shown in the figure 2. Then calculate the centroid positions of the left and right particles in each image, determine the displacement size (in pixels) between adjacent particles, and based on the known camera exposure time, calculate the speed of particle motion.

3. High Speed Particle Tracking Measurement Experiment

3.1 Experimental setup

The high-speed particle tracking measurement experiment is a high-speed particle tracking measurement system that monitors the splashed debris of the sample container during the falling process, and measures and calculates the motion speed, motion angle, and splashing trajectory of the gravel particles.

The observation object is the entire sampling process of the sampling front-end, and the observed area includes the sample slot, the sampling front-end, and the entire sample channel. The observation area includes a transparent organic glass rectangular prism with a sample slot size of 300mm x 150mm x (100mm); The size range of the sampling front-end and sample channel is approximately 70mm x 250mm x 300mm in a transparent area. The entire observation area is placed in a transparent organic glass bucket with a diameter of 500 * 600mm. During the observation process, the sampling front end will sink into the sample slot. During the sampling process, the sample particles move from bottom to top. The tested object is the particles of the stellar soil sample, and it is necessary to visually recognize and classify particles of different sizes. The maximum observed particle velocity is ≤ 10m/s. The following diagram is a schematic diagram of high-speed particle measurement sampling:

The hardware consists of an ultra high speed pulse camera, trigger module, dedicated tooling, lighting source, mobile workstation, and cable. The ultra high speed pulse camera is a 1 million pixel resolution ultra-high frame rate measurement camera used for high-speed particle image acquisition. According to the particle speed range, the pulse camera acquisition frequency is set to 2000Hz.

The particle tracking measurement system consists of main equipment such as mechanical support system, image acquisition and control system, lighting system, and data post-processing analysis system, which can achieve high-speed video recording of particle motion process. The mechanical support system can fix and protect the lighting and visual system, the image acquisition system can accept external start trigger commands, and the multi camera vision system can synchronize 1000Hz high-speed real-time image acquisition and storage, with a storage time of nearly 12 seconds. The lighting system provides stable high brightness lighting. After the data collection is completed, the recorded data of the multi camera vision system is read back through post-processing analysis software, and the spatial coordinates, motion parameters, and motion trajectory tracking recovery of the particle image are achieved through the calibration of the internal and external parameters of the multi camera system in the early stage.

The image acquisition and control system includes 5 cameras, including one high-resolution high-speed storage color camera and four black and white high-speed storage cameras. Two black and white cameras are installed vertically, achieving a wide field of view coverage through field of view splicing. A single color camera and two sets of binocular splicing black and white cameras provide three directional perspectives, achieving wide field coverage for particle trajectory tracking measurement.

3.2 Calibration of camera system

Considering that the visual system passes through a cylindrical glass barrel to observe the target and produces an approximate barrel distortion effect, the radial error model of the lens distortion model in the visual system can be characterized. Therefore, when calibrating the stereo vision system with cylindrical barrel glass, a direct calibration method is adopted, which uniformly calibrates the cylindrical glass barrel and lens distortion. The specific operation method is to collect multiple chessboard calibration board images under different postures, as shown in the following figure 3, to achieve calibration of lens distortion and cylindrical barrel glass distortion in the camera.

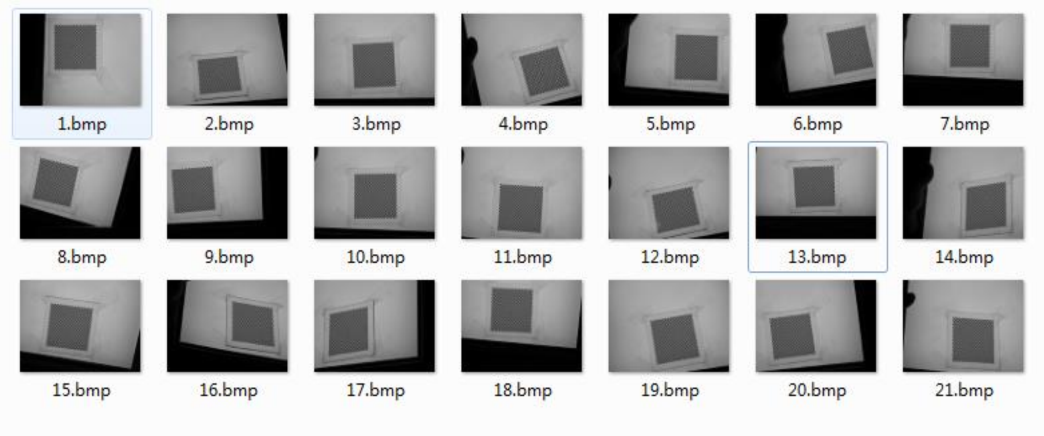

Figure 3: Image Collection of Checkerboard Checkers

Find corner points for images with different poses, as shown in the following figure 4. Combine the corner points found with the properties of the calibration board itself to achieve camera calibration.

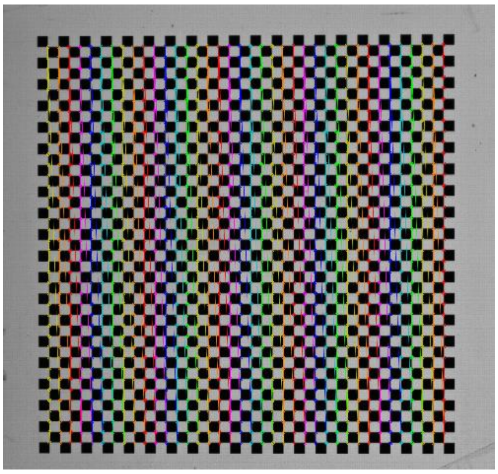

Figure 4: Checkerboard Corner Search Diagram

3.3 High speed particle tracking measurement

The main steps of the high-speed particle tracking measurement experiment are as follows:
(1) 5 cameras collect particle motion images and store image data;
(2) Decoding camera images using particle tracking measurement software;
(3) Data homography calibration;
(4) Particle flow calculation;
(5) Continuous tracking calculation of particle information+saving;
(6) Read back historical data.

Before setting up the experimental equipment, use a calibration board to calibrate the camera's internal parameters; After completing the camera setup, use a calibration board to calibrate the camera's external parameters and determine the positional relationship between the cameras. Open the camera synchronization control software, connect the camera online, and complete the synchronization collection of images.

The method of using particle tracking measurement calculates the motion velocity of the same particle between any two frames by manually selecting particles. When tracking in consecutive frames, the average velocity of the particles is calculated.

To solve the velocity of particles in space, it is necessary to obtain a comprehensive calculation of the front and side camera images. Abandoning the side camera images will result in a lack of dimensional information for spatial particles. Therefore, in this calculation, the first step is to calculate the frame rate and image scale information of the side camera.

The calculation of side camera scale is shown in the table 1.

Table 1: Calculation of Side Camera Scale

No	True width (mm)	Pixel width	Unit pixel distance
①	50	227	0.220264317
②	13	59	0.220338983
③	30	141	0.212765957
④	28	141	0.19858156
⑤	32	161	0.198757764

Calculate weighted mean: unit pixel distance=0.21mm.

Side camera frame rate calculation:

Based on the front camera, the frame rate of the side camera is calculated to be 66FPS. The splashing particles selected are as follows (frame 4481), with a total of 10 particles (as shown in Figure 5).

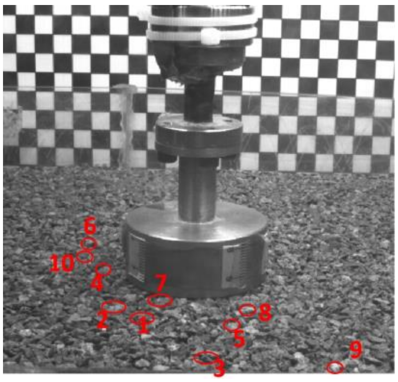

Figure 5: Experimental Selection of 10 Particles and Their Distribution

Place the particle positions obtained from multiple frames of particle images in the same spatial coordinate system to obtain particle trajectories as shown in the following figure 6:

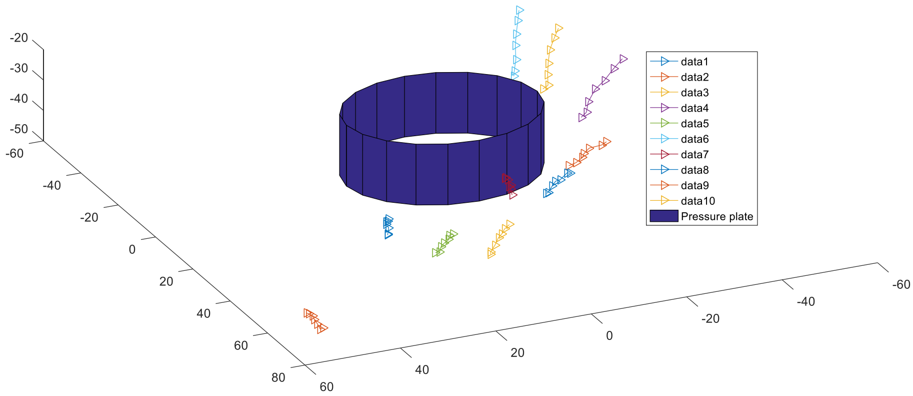

Figure 6: Particle Trajectories in The Same Spatial Coordinate System

The accuracy of particle localization is shown in the table 2:

Table 2: Positioning Accuracy of Particles

No	Test Items	Standard	Test Method	Test Results
1	Manually selecting particles to calculate	positioning accuracy of ± 0.2mm	Manually selecting the same particle between two frames	Test passed
2	Continuous tracking calculation of particle velocity	positioning accuracy of ± 0.2mm	Using software to track particles in sequence images and calculate the average particle velocity	Test passed

The high-speed particle tracking measurement system can monitor and identify the trajectory of particles moving at high speed, with a tracking particle spatial positioning accuracy of ± 0.2mm. The measured particle velocity is between 0-2.0m/s, with a measurement error of 10%. The data is real and reliable, providing an effective theoretical basis for the measurement and research of high-speed particles.

Based on experimental location data, select particle sequence images within a certain time period to test particle tracking performance (Figure 7).

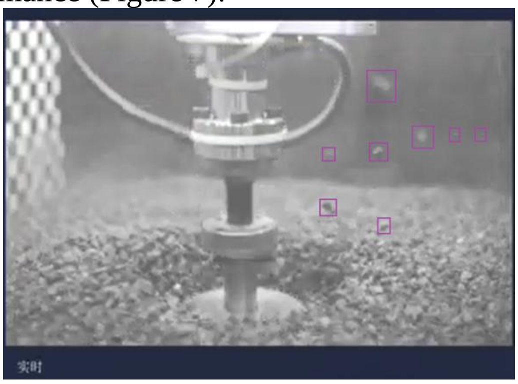

Figure 7: Particle Tracking Rendering

4. Conclusion

In the field of high-speed particle tracking measurement, in order to achieve accurate measurement of particle motion trajectory and velocity, this study constructs a high-speed particle tracking measurement method based on an ultra high speed pulse camera. This method simulates the movement of high-speed particles by monitoring the splashed debris during the falling process in the sample container. It can measure and calculate the movement speed, angle, and splashing trajectory of the gravel particles. The method mainly adopts the method of frame difference before and after to achieve target recognition and positioning. Through experimental data testing, the accuracy of the system is within the expected range, and the results of particle velocity calculation meet expectations. This achievement provides effective technical support for subsequent research on tracking and measurement of high-speed particles.

High speed particle tracking measurement has important value in scientific research and engineering applications. The measurement method based on ultra high speed pulse camera proposed by this research institute not only captures the motion trajectory of high-speed particles during the experimental process, but also obtains particle velocity, angle and other information through accurate image processing and analysis algorithms, providing a powerful tool for in-depth research on particle motion behavior. However, there are also some potential challenges and directions for improvement in this study. For example, the stability and repeatability of the system under different conditions need to be further validated to ensure the reliability of the measurement results. In addition, considering factors such as particle shape and interactions between particles can also help improve measurement accuracy and the applicability of experiments.

Acknowledgments

This work is supported by Technological Innovation 2030- Major Project of "New Generation Artificial Intelligence" (2021ZD0109804) Funding

References

[1] Andreopoulos A, Kashyap H J, Nayak T K, Amir A and Flickner M D. 2018. A low power, high throughput, fully event-based stereo system, Proceedings of 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition. Salt Lake City, USA: IEEE: 7532- 7542

[2] Guo M H, Ding R X and Chen S S. 2016. Live demonstration: a dynamic vision sensor with direct logarithmic output and full-frame pictureon-demand, 2016. IEEE International Symposium on Circuits and System. Montreal, Canada: IEEE: 456

[3] Gyongy I, Dutton N A W and Henderson R K. 2018. Single-photon tracking for high-speed vision. Sensors, 18(2): #323

[4] Han J, Zhou C, Duan P Q, Tang Y H, Xu C, Xu C, Huang T J and Shi B X. 2020. Neuromorphic camera guided high dynamic range imaging, Proceedings of 2020 IEEE / CVF Conference on Computer Vision and Pattern Recognition. Seattle, USA: IEEE: 1727-1736

[5] Baldwin R W, Almatrafi M, Asari V and Hirakawa K. 2020. Event probability mask (EPM) and event denoising convolutional neural network (EDnCNN) for neuromorphic cameras, Proceedings of 2020 IEEE/ CVF Conference on Computer Vision and Pattern Recognition. Seattle, USA: IEEE: 1698-1707

[6] T-G Fang, R E Coverdill, C-F F Lee, and R A White, 'Effect of the Injection Angle on Liquid Spray Development in a High Speed Direct Injection Optica Diesel Engine, in Proceedings of the Institution Of Mechanical Engineers, Part D: Journal of Automotive Engineering, 2009, pp. 77-92

[7] O. Feldmann, E.H.F. Mayinger and P. Gebhard, 'Evaluation of Pulsed Laser Holograms of Flashing Sprays By digital image processing and holographic particle image velocimetry', Nuclear Engineering and Design, 1998, 184: 239-252

[8] M. Reza Soltani, Kaveh Ghorbanian, Mehdi Ashjaee, and Mohammad R. Morad, 'Pda and Neural Network Investment of Swirl Spray Interaction Phenomena', Part. Syst. Character. (2005), 192-206

[9] R, P. C. Zegers, C. C. M. Luijten, N. J. Dam, and L. P. H. de Goey, 'Pre and Post Injection Flow Characterization

in a Heavy Duty Diesel Engine Using High Speed Piv', Experiments in Fluids (2012), 731-746
[10] Li Jianing, Tian Yonghong 2021. Research progress and application review of neuromorphic visual sensors Journal of Computer Science, 44 (6): 1258-1286 [DOI: 10 11897/SP. J. 1016 January 258, 2021
[11] Sang Yongsheng, Li Renhao, Li Yaoqian, Wang Qiangwei, Mao Yao 2019. Research on Neuromorphic Visual Sensors and Their Applications Journal of the Internet of Things, 3 (4): 63-71
[12] Wang Cheng, Chen Feng, Wen Desheng, Lei Hao, Song Zongxi, Zhao Hangfang 2021. Progress in Visual Sensing Imaging Technology and Data Processing Chinese Journal of Image and Graphics, 26 (6): 1450-1469
[13] Zhao J, Xiong R Q, Liu H F, Zhang J and Huang T J. 2021b. Spk2ImgNet: learning to reconstruct dynamic scene from continuous spike stream/ / Proceedings of 2021 IEEE/ CVF Conference on Computer Vision and Pattern Recognition. Nashville, USA: IEEE: 11991-12000 [DOI: 10. 1109 / CVPR46437. 2021. 01182]
[14] Zhao J, Xiong R Q, Zhao R, Wang J, Ma S W and Huang T J. 2020b. Motion estimation for spike camera data sequence via spike interval analysis/ / Proceedings of 2020 IEEE International Conference on Visual Communications and Image Processing. Macau, China: IEEE: 371-374 [DOI: 10. 1109 / VCIP49819. 2020. 9301840]
[15] Zheng Y J, Zheng L X, Yu Z F, Shi B X, Tian Y H and Huang T J. 2021. High-speed image reconstruction through short-term plasticity for spiking cameras/ / Proceedings of 2021 IEEE/ CVF Conference on Computer Vision and Pattern Recognition. Nashville,USA: IEEE: 6354-6363 [DOI: 10. 1109 / CVPR46437. 2021. 00629]
[16] Huang Tiejun, Yu Zhaofei, Li Yuan, Shi Boxin, Xiong Ruiqin, Ma Lei, Wang Wei 2022. Progress in Pulse Vision Research Chinese Journal of Image and Graphics, 27 (06): 1823-1839
[17] Huang Tiejun 2022. Principles of Pulse Continuous Photography and Verification of Ultra High Speed and High Dynamic Imaging, Journal of Electronics. 50 (12): 2919-2927