Measurement of Bullet Velocity Parameter from High-speed Sequential Images

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Abstract. The bullet velocity parameter is the base of the next analysis of many impact experiments. A complete and rapid measurement of velocity parameter before and after an impact of the projectile on the target is a problem to be solved. We proposed a method aiming at measuring the bullet velocity parameter from high-speed sequential images, completely and fast. We firstly set up the high-speed camera sensor network for grabbing and storing of high-speed sequential images. It contained two high-speed cameras, a synchronous control system, two master-slave computers to control other systems, and the supplement light system. Subsequently, a surveying control network was constructed to solve the parameters of videogrammetry. 3D reconstruction was applied to the solution of the bullet center 3D coordinates, and the bullet velocity parameter was finally solved by the approach of time difference. The experiment of measurement of the bullet velocity was done successfully. The bullet velocity parameter we measured was provided to the criminal investigation department.

1. Introduction

Videogrammetry is a powerful tool for three-dimensional velocity field measurements [3]. It is wildly used in many scenes, such as three-dimensional velocity measurements in liquids [3], powder snow avalanches flow velocity measurement [4], structural progressive collapse and velocity measurement [7], and velocity measurement in sports [11-12]. High-speed Videogrammetry is so flexible that we arrange the experiment according to the scene. The measurement result of bullet velocity parameter is the basis of other analysis [8]. The approach of the bullet velocity measurement has been developed for many years.

The method of detecting screens [9] had measured in-flight bullet velocity for decades. Optoelectronic methods based on light screen sensor [1-2, 5] are limited by the spatial layout of the light screen sensor, and moreover, the measurement results exist errors. Tian in 2020 [10] proposed a method based on photoelectric detection and verified it could measure the flight speed parameter, and it was not only seriously restricted by the spatial layout of the light screen sensor but also had a complex measurement process. Moreover, the experiment result got about 3 mm error. Another method for measurement of bullet velocity was also applied widely. Jaafar et al. presented velocity measurement based on high-speed imaging system on an impact test [6]. The obliquity of free flight motion and the camera settings such as the size of the viewing area and exposure time were the key factor for the impact test to measure velocity. Schyma et al. used a high-speed camera to measure bullet velocity and analyzed the factors affecting the accuracy of velocity measurement [8]. That the bullet’s trajectory could be identified decided the reliability of the measurements and the length of the measured distance played a secondary role for measurement accuracy when the bullet was sharply imaged. The measurement
method based on a high-speed camera was convenient to grab sequential images. Compared with opto-electronic methods, it was flexible enough to satisfy different scene and had no limitation to spatial layout of hardware. However, a high-speed camera to measure bullet velocity could only get a 2D result. It was less accurate than 3D measurement. Furthermore, the reliable and complete measurement of the bullet’s speed of the whole process is required on a bullet impact experiment.

We proposed a method based on videogrammetry for the measurement of bullet velocity. The high-speed camera sensor network was set up to grab and store high-speed sequential images. The parameters of videogrammetry that 3D reconstruction needed for the solution of the bullet center 3D coordinates could be solved after a surveying control network was constructed. And we used the approach of time difference to solve the bullet velocity parameter. The proposed method detected and tracked the projectile on the sequential images, made 3D measurement reliable. The bullet velocity was successfully calculated both before and after bullet impacting on the glass target. The integrity of the whole measurement experiment was guaranteed. We used 3D measurement acquiring more accurate measurement result.

2. Methodology

2.1. The Proposed Method

The proposed method divided three part to measure the velocity: 1) set up the high-speed camera sensor network, 2) construct surveying control network, 3) 3D reconstruction and solve the bullet velocity parameter. With the supplement light system functioning, two high-speed cameras, synchronously aim at capturing of high-speed sequential images when the bullet comes out at the very high speed. A 3D high-speed videogrammetry high-speed camera sensor network is shown in Figure 1.

![Figure 1. 3D High-speed Videogrammetry High-speed Camera Sensor Network System for Bullet Velocity Measurement.](image)

The high-speed camera sensor network contained two high-speed cameras, a synchronous controller, two master-slave computers to control other systems, and the supplement light system. We set up the high-speed camera sensor network for grabbing and storing of high-speed sequential images. Before the sequential images was stored, we should construct the surveying control network as figure 2 was shown.
As it was shown in figure 2, actual distance between any two dots was 20 mm on calibration board. The first dot on the calibration board was the origin of the spatial rectangular coordinate system, and the Z axis was the vertical on the calibration board. The X axis was the horizontal direction on the calibration board and the vertical downward of the calibration board is Y axis. The points which were closed to the field of view were selected as the control points. Therefore, the exterior orientation elements could be calculated by control points and subsequently calculated the rotation matrix R. Before three-dimensional reconstruction, we detected and tracked the centroid of the bullet target on the left and right sequential images. The interior orientation elements were calculated by camera calibration aforesaid. The method of 3D reconstruction calculated the target 3D coordinate vector. Finally, the bullet velocity parameter was solved by the approach of time difference. Figure 3 was the flow of 3D construction.

3. Experimental and Result Analysis
The experimental grabbed and stored the left and right sequential images before and after the impact of the projectile on the glass target. They were figure 4 and figure 5, respectively.
Figure 4. (a), (b) and (c) were the left images before the impact on the glass target; (d), (e) and (f) were the right images before the impact on the glass target.

Figure 5. The top was the left sequential images after the impact on the glass target and the bottom was the right sequential images after the impact on the glass target.

3.1 Experimental Environment

The experimental environment was that two high-speed cameras with resolution and frame frequency of 320×320@2681 fps was connected by the trigger line of the synchronous controller, respectively. The host computer linked the slave computer by a netting twine, and the host connected a high-speed camera by two CoaXPress data transfer interfaces. The slave was the same. The host connected synchronous controller by a trigger line. Two halogen lamps made up the lighting system to fill the scene and the scene was shown as figure 6.
3.2 Result Analysis

Before the projectile of the impact on the glass target, the 3D centroid coordinates the proposed method calculated were listed in table 1. The measurement result of the bullet velocity parameter didn’t change much.

Table 1. Results of the bullet velocity parameter before the bullet hit the glass target.

| Index | X(m)       | Y(m)       | Z(m)       | Displacement(m) | Velocity(m/s) |
|-------|------------|------------|------------|----------------|---------------|
| 0     | 900.573584 | 600.357679 | 99.855551  |                |               |
| 1     | 900.580337 | 600.361205 | 99.939116  | 0.083912       | 224.97        |
| 2     | 900.58784  | 600.364389 | 100.023767 | 0.085043       | 228.00        |

After the projectile of the impact on the glass target, the 3D centroid coordinates measured by the proposed method were shown as table 2. We analyzed that the bullet velocity changed a little.

Table 2. Results of the bullet velocity parameter after the bullet impacted the glass target.

| Index | X(m)       | Y(m)       | Z(m)       | Displacement(m) | Velocity(m/s) |
|-------|------------|------------|------------|----------------|---------------|
| 0     | 900.5927   | 600.3539   | 100.0259   | 0.015257       | 40.90         |
| 1     | 900.592    | 600.35     | 100.0112   | 0.018669       | 50.05         |
| 2     | 900.5923   | 600.3432   | 99.98593   | 0.007667       | 20.56         |
| 3     | 900.5916   | 600.3387   | 99.97162   | 0.015026       | 40.28         |
| 4     | 900.5908   | 600.3351   | 99.95996   | 0.012235       | 32.80         |
| 5     | 900.5903   | 600.3319   | 99.94805   | 0.012348       | 33.10         |
| 6     | 900.5904   | 600.3282   | 99.93281   | 0.01567        | 42.01         |
| 7     | 900.5903   | 600.3249   | 99.9211    | 0.012194       | 32.69         |
| 8     | 900.59      | 600.3214   | 99.90792   | 0.013622       | 36.52         |
| 9     | 900.5894   | 600.318    | 99.89472   | 0.013649       | 36.59         |
| 10    | 900.5894   | 600.3146   | 99.88261   | 0.012589       | 33.75         |
The time difference method was applied to calculate the bullet velocity before and after an impact on the glass target. Before the projectile of an impact on the glass target, the velocity variation was not large, and the velocity fitting curve was slightly upward, but because of the small number of frames collected, the upward trend was not certain; After the projectile of an impact on the glass target, the bullet velocity of the second frame and the third frame changed greatly, because the bullet in the sequential images had the drag shadow, which was easy to cause the bullet centroid extraction inaccurate. The change of the other frames was relatively gentle, the speed fitting curve basically showed the downward trend. It was in line with the target object deceleration motion law.

Before and after the projectile of the impact on the glass target, measurement results of the average bullet velocity were 226.48 m/s and 36.25 m/s, respectively. That was in line with the principle that the energy of motion of bullet loss, and its speed reduced. Furthermore, the measurement results of this experiment met those of most literatures.

4. Conclusion
This paper presented a method for measuring bullet velocity from high-speed sequence images. The proposed method set up a high-speed camera sensor network to grab and store the sequence images before and after the bullet impact on the glass target. The surveying control network solved the outer orientation elements, which were the parameters of 3D reconstruction. We accurately extracted 2D coordinate of the bullet target centroid and tracked the sequential images. After calculating the internal orientation elements of the high-speed camera in advance, the 3D centroid coordinate vector of the bullet target was calculated by using the space intersection. That was the process of 3D reconstruction. The bullet velocity parameters before and after the projectile impacted on the glass target were calculated completely. We concluded that the measurement results of the bullet velocity parameter conformed to the law of deceleration motion of the bullet target. Furthermore, the measurement results of this experiment also met those of most research. It was found that there was an error in measuring the velocity of the bullet when the target had a long shadow. The problem should be solved in the future research using the approach of outlier elimination. The experimental results of this paper provided the basis for criminal investigation and analysis.

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