Research on rapid prediction method of projectile impact point

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ABSTRACT

In the test of explosion height and dynamic parameters, pre-obtaining the relatively accurate position of the projectile is essential. However, at present, it is impossible to provide a forecast value for the impact point of each projectile through methods such as firing table, gun position reconnaissance and calibration radar or ballistic radar. In order to improve the fast and accurate prediction ability of projectile impact point and realize the accurate prediction of each projectile, this paper proposes a method of establishing simulated ballistic trajectory based on the measured data of the gun position and secondary correction of the ballistic data based on the ballistic radar. Compared with the traditional method, the method has a more accurate prediction of the coordinates of the impact point due to the use of the measured data of the gun position and the radar. The test results show that after using this method, the entire forecast time can be controlled within 8 seconds, and the accuracy of distance and direction is improved. The equipment in the bomb drop area can complete corresponding actions according to the forecast data, and improve the data admission rate.

Keywords: Impact point; rapid forecast; secondary correction; measured data; simulated ballistics

1. INTRODUCTION

At present, in the explosion height test of the shooting range test, the detonator is mainly equipped on the forced bomb, grenade and rocket[1]. Because it requires high precision, a high-speed camera is generally used to measure the distance from the explosion point of action in the bomb drop area 1 km. However, in the actual test, assuming that the focal length of the camera is 150mm, the line field of view can cover 133m, and nearly 30% of the projectiles will be out of the field of view[2]. Statistics show that the data acceptance rate is about 70%[3]. The reason is that these devices use waiting measurement, and the test area is small. However, if the projectiles may fall and have a high prediction accuracy, so that the explosion point measurement device points to the prediction point, the testing capability of the device will be improved. In addition, dynamic test parameters such as the angle of attack, falling speed, and fragmentation speed of the projectile need to be obtained first.

To the relatively accurate impact point of the projectile, it is planned to use high-speed video recording or radar testing to complete the project. Therefore, improving the ability to quickly and accurately predict the impact is crucial to the improvement of other testing capabilities of the range.

At present, through the artillery position reconnaissance calibration radar and ballistic radar, the impact point can be extrapolated according to the data at the end of the ballistic trajectory[4], and the accuracy is high, but the forecast value cannot be given in advance. However, although the existing shooting table method can obtain the theoretical landing point and spread range of the projectile impact point under standard conditions[5-7], it is impossible to estimate each projectile due to individual differences, such as the influence of factors such as the amount of charge, weather conditions and artillery rifling hit point.

In order to quickly and accurately predict the location of the explosion point, this paper mainly focuses on non-extended range projectiles such as forced bombs and grenades, and takes the drop point test of a certain type of projectile as an example. The test equipment mainly includes initial velocity, ballistic radar, ground weather, and drop point measurement. Fast and accurate prediction method of explosion point is proposed. Based on the real-time test data of the gun position, on the basis of the first indicator projectile, the equivalent ballistic coefficient is obtained by using the external ballistic simulation method, and the ballistic model is established; The initial segment ballistic data provided by the radar in real time is corrected twice to complete the fast and accurate prediction of the impact point of the projectile. The entire forecast time can be controlled within 8 seconds, and the equipment in the bomb drop area can complete corresponding actions

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according to the forecast data, providing an effective indication method for testing the bomb drop point and some dynamic parameters.

2. MATHEMATICAL MODEL OF OUTER BALLISTICS

2.1 Motion model of projectile centroid

The nutation angle of the projectile is always small for flight stability, so it can be described by the equation of motion of the particle when studying the projectile motion. The mass point motion equation does not consider the influence of the earth's rotation and the change of gravitational acceleration with latitude, but consider the change of gravitational acceleration with height and the influence of wind and drift current, and give the mass center momentum equation system with the ground rectangular coordinate system as the independent variable[8, 9]:

$$\begin{cases} \frac{dv_x}{dt} = -\frac{\pi}{8000} c\rho C_{xon}(\frac{v_r}{a}) v_r (v_x - w_x) \\ \frac{dv_y}{dt} = -\frac{\pi}{8000} c\rho C_{xon}(\frac{v_r}{a}) v_r v_y - g \\ \frac{dv_z}{dt} = -\frac{\pi}{8000} c\rho C_{xon}(\frac{v_r}{a}) v_r (v_z - w_z) + k_{zp} B \frac{v_x}{v^2} \\ \frac{dx}{dt} = v_x \\ \frac{dy}{dt} = v_y \\ \frac{dz}{dt} = v_z \end{cases} \tag{1}$$

2.2 Air temperature model

In the troposphere,

$$\tau = \tau_{on} - 0.006328h \tag{2}$$

where τ_{on} is the surface air temperature under non-standard meteorological conditions, and h is the plane height. There are different analytical formulas in the substratosphere and stratosphere. Due to the limited elevation of the forced bomb, this paper will not repeat them

2.3 Gravitational acceleration model

$$g = \frac{g_0}{(1 + h / R_0)^2} \tag{3}$$

In formula (3), g_0 is the surface gravitational acceleration, R_0 is the radius of the earth, and g is the gravitational acceleration at height h.

2.4 Wind speed model

$$v = v_0 \left(h / h_0 \right)^{\alpha} \tag{4}$$

In formula (4), v is the wind speed at the height h from the ground, v_0 is the wind speed at h_0 in the case of real-time measurement[10]. It is considered that the wind direction does not change during the ballistic process. And α is the ground roughness, and takes the value of 0.12 on the plain ground.

3. DESCRIPTION OF THE SIMULATION PROGRAM

(1) The piecewise function of the air resistance coefficient[11] is written by the interpolation method, and the air resistance coefficient at each Mach number can be obtained.

(2) For the density of air, which changes with temperature, pressure and altitude, the corresponding density function, the corresponding variable acceleration of gravity, speed of sound, and air temperature change with altitude are in section 2. Using the fourth-order Runge-Kutta method with fixed step size, call the corresponding sub-function to solve the differential equation system of the movement of the center of mass of the projectile, and obtain the coordinates in the coordinate system of the shooting range, as shown in Figure 1.

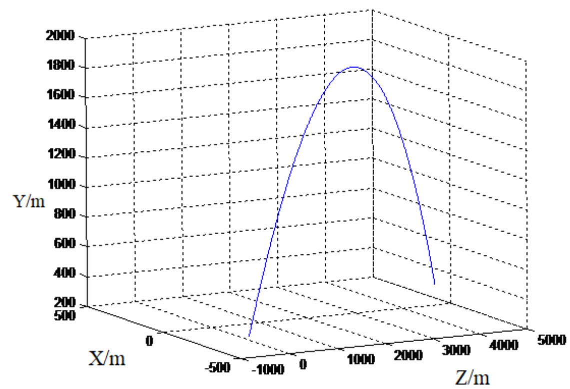

Figure 1. Ballistic curve diagram in the coordinate system of the shooting range.

4. SIMULATION OF IMPACT POINT PREDICTION

4.1 Data sources

Table 1 shows the test data of the ground impact point of a certain type of projectile with 18 rounds. The equipment participating in the test mainly included initial velocity radar, ballistic radar, ground meteorology and impact point measurement equipment.

Table 1. Parameters of initial measurement and true value of impact point measurement.

No.	Initial velocity m/s	Wind direction°	Wind velocity m/s	Air temperature ℃	Air pressure MPa	Z(m)	X(m)
1	181.8	332	1.1	35.4	961.0	4684.4	-68
2	181.6	303	2.5	35.8	961.0	4610.2	-71.4
:	:	:	:	:	:	:	:
18	185.9	11	0.9	37	959.7	4782.0	-26.2

The muzzle velocity-impact distance distribution was obtained, as shown in Figure 2.

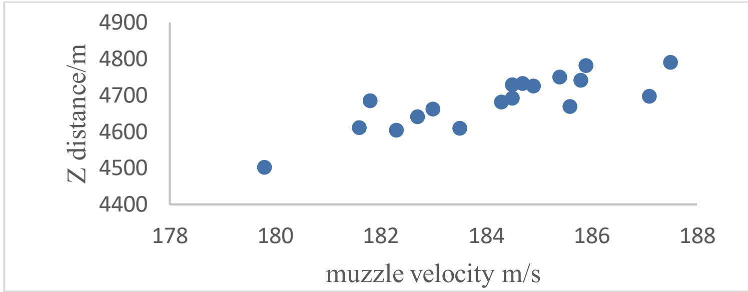

Figure 2. Schematic diagram of the distribution of muzzle velocity - impact point distance.

It can be seen from the figure that the distance between the two groups of projectiles was about 300 meters away, and when the initial velocity was basically the same, the impact point may also be quite different. As shown in the figure, when the initial velocity was around 286m/s, the distance also reached about 150m, which was not conducive to the measurement of small-scale testing instruments. Based on the real-time measurement data, this paper discusses the rapid prediction method of the impact point of the projectile.

4.2 Prediction method of ground impact point

(1) We used the real-time test data as the basis (muzzle velocity and shooting angle), and added the meteorological measurement value to facilitate the comparison with the ballistic radar (a data can be provided every 0.05 s). The simulation time step was 0.05 s, and the actual flight time of the projectile was about 46s, the simulation time was set to 47s. The simulation termination condition was that the projectile height was less than the launch height, and the initial ballistic coefficient c_0 was set as 1.3;

(2) Then the impact point data of the first projectile was added to correct the ballistic coefficient, so that the impact point simulated by the model was close to the measured value of the first shot (mainly in distance). In addition, we determined the ballistic coefficient, and obtained the equivalent ballistic coefficient of current environment including other non-measurement factors;

(3) After that, the first impact point was calculated according to the real-time measured initial velocity, wind speed, wind direction, air temperature and air pressure parameters by the obtained ballistic coefficient;

(4) Afterwards, we used the initial segment data provided by the ballistic radar in real time for secondary correction that is, comparing the simulation data with the data measured by the ballistic radar. The correction method was as follows: the discrete data of the simulation and the ballistic radar was firstly taken out, respectively, then the third second data of the simulation was taken as the benchmark. After that, we compared with the distances, searched for the points similar to the ballistic radar, and arranged them in the corresponding order based on this data. The first simulation data and ballistic radar data is as shown in Table 2.

Table 2. The first simulation data and ballistic radar data.

First simulation data				**Ballistic Radar Data**			
Time/s	Distance Z/m	Height Y/m	Direction X/m	Time/s	Distance Z/m	Height Y/m	Direction X/m
3	*-180.771*	872.8016	-431.433	3	-190.949	859.9793	-438.775
3.05	-171.274	880.8869	-430.667	3.05	*-181.828*	867.4335	-438.041
3.1	-161.789	888.9376	-429.902	3.1	-172.717	874.865	-437.307
:	:	:	:	:	:	:	:
5	190.082	1169.664	-401.435	5	167.7876	1138.916	-410.798

Through the comparison of distance, the 3rd second data of ballistic radar was excluded. The selected data is shown in Table 3.

Table 3. Comparison between the first simulation data and ballistic radar data.

First simulation data				Ballistic Radar Data			
Time/s	Distance Z/m	Height Y/m	Direction X/m	Time/s	Distance Z/m	Height Y/m	Direction X/m
3	*-180.771*	*872.8016*	*-431.433*	3.05	*-181.828*	*867.4335*	*-438.041*
3.05	-171.274	880.8869	-430.667	3.1	-172.717	874.865	-437.307
3.1	-161.789	888.9376	-429.902	3.15	-163.613	882.2725	-436.574
:	:	:	:	:	:	:	:
4.95	181.005	1162.873	-402.171	5	167.7876	1138.916	-410.798

From the 4th second, the distance difference in the direction was divided by the corresponding simulation time to get the speed as shown in Table 4.

Table 4. Speed correction values in each direction.

Time/s	**Distance Z difference /m**	**Distance Y difference /m**	**Distance X difference /m**	**Distance Z difference/Time m/s**	**Distance Y difference/Time m/s**	**Distance X difference/Time m/s**
4	7.96953	16.51804	7.44995	1.99238	4.12951	1.86249
4.05	8.27079	16.97514	7.50299	2.04217	4.19139	1.85259
:	:	:	:	:	:	:
4.95	13.21747	23.95770	8.626212	2.67020	4.83994	1.74267
Average corrected velocity value in 4-4.95 seconds (m/s)				*2.3682*	*4.5505*	*1.7922*

The average corrected velocity value within 4-4.95 seconds was obtained. In this ballistic model, various other non-standard factors in the actual ballistic environment were converted into the equivalent initial velocity as the correction value of the projectile initial velocity in each component

(5) The initial value of each component was corrected by $\bar{v}_{x0}=v_0\cos\theta_0\cos\varphi_0-v_{x-t45}$, $\bar{v}_{y0}=v_0\sin\theta_0-v_{y-t45}$, $\bar{v}_{z0}=v_0\cos\theta_0\sin\varphi_0-v_{z-t45}$. Then we performed secondary simulation to obtain the predicted coordinate value of the impact point. Besides, there were several reasons for choosing the 3-5 second segment data of ballistic radar for comparison and correction:

(a) The method of comparing the initial velocity with the data of a certain type of ballistic radar is used to test the muzzle velocity, because the station is placed behind the artillery side during the test, and the first 2-3 seconds is a process of servo self-tracking. After the 3rd second, the automatically tracked data is relatively stable;

(b) The need for rapid forecasting requires sufficient time for the equipment in the drop zone to complete the rotation of the field of view. If the terminal ballistic data is used, the forecasting purpose cannot be achieved;

(c) By calculating and comparing a large amount of data in 3-10 seconds, we can see that the data in 3-5 seconds has better prediction results.

4.3 Simulation results

According to the above method, the measured data was simulated. Here, the impact point elevation result was the same elevation as the gun position, and the coordinate values of the impact point distance and direction under the shooting range coordinate system were obtained, as shown in Tables 5 and 6.

Table 5. Prediction results of the first group of projectile impact points.

No.	**First error value**		**Quadratic error value (step size 0.05)**		**Quadratic error value (step size 0.01)**		**Remark**
	Z/m	X/m	Z/m	X/m	Z/m	X/m	
1	0	31	Determine the equivalent ballistic coefficient c=1.3989				
2	68.8	46.4	5.8	-3.6	*5.8*	*-4.6*	
3	45	49.6	-49	-0.4	*-46*	*-0.4*	
4	87.3	34.8	-12.7	0.8	*-8.7*	*-0.2*	
5	110.9	-15.9	17.9	-5.9	*20.9*	*-5.9*	
			——				
14	86.3	-79.7	24.3	-70.7	*27.3*	*-70.7*	
15	120.3	-2.6	27.3	-9.6	*29.3*	*-9.6*	
16	42	-61.6	-16	-40.6	*-13*	*-40.6*	
17	41	-19.5	-51	-14.5	*-49*	*-15.5*	furthest
18	86.1	-97.7	22.1	-63.7	*25.1*	*-63.7*	

Table 6. The second group of projectile impact point prediction results.

No.	**First error value**		**Quadratic error value (step size 0.05)**		**Quadratic error value (step size 0.01)**		**Remark**
	Z/m	X/m	Z/m	X/m	Z/m	X/m	
1	0	31	Determine the equivalent ballistic coefficient c=1.3989				
2	68.8	46.4	5.8	-3.6	*5.8*	*-4.6*	nearest
			——				
16	94.8	-32.2	-13.2	-8.2	*-10.2*	*-8.2*	
17	-28.5	-17.3	-50.5	-6.3	*-45.5*	*-6.3*	
18	57.3	27.2	18.3	23.2	*21.3*	*23.2*	

Finally, the error between the two simulation results and the actual measured value were obtained, as shown in Figures 3 and 4.

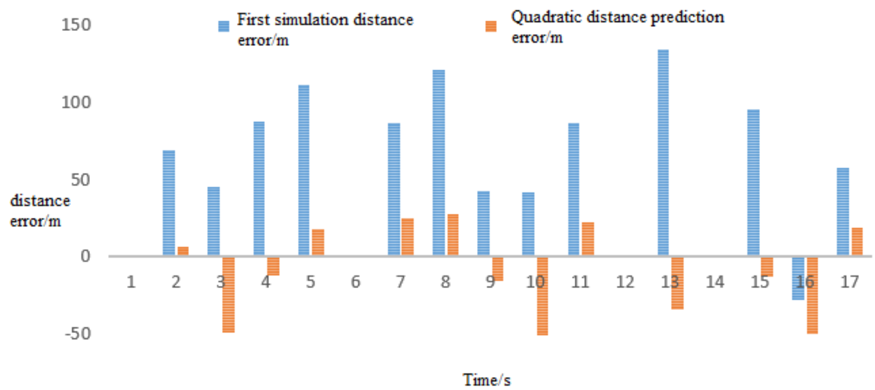

Figure 3. Prediction error of impact point distance.

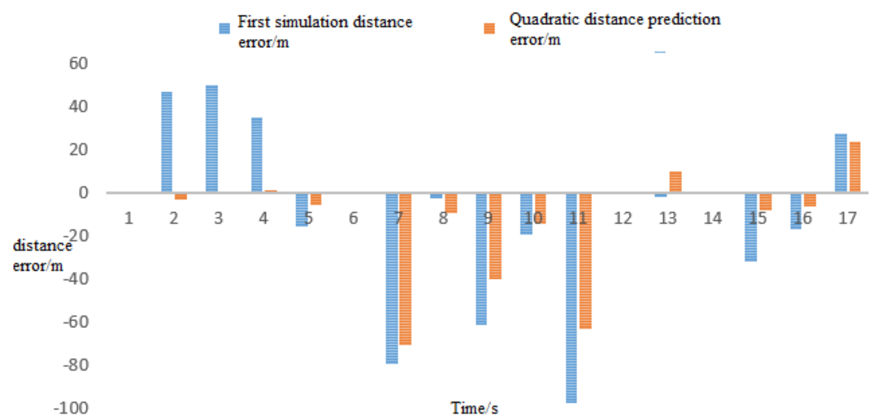

Figure 4. Prediction error of impact point direction.

It can be seen from Figure 4 that after the second correction, the prediction accuracy in distance and direction has been greatly improved. When a fixed step size of 0.05 seconds was selected, the error in distance could be controlled within 51 meters; when the root mean square error was 30.2 m, the direction error could be controlled within 70.7 m, and the root mean square error is 30.1 m. Because there was no time matching problem in the secondary simulation, a fixed step size of 0.01 seconds could be selected to improve the accuracy of the ballistic solution. The error could be controlled within 49 meters, the root mean square error was 29.2 m, and the direction error and root mean square error were the same as when the step size was 0.05 seconds. Individual projectiles would have large errors in the direction, mainly due to the errors brought by the model, and there may also be unpredictable factors such as gusts, jets, and random winds that have a greater impact on the direction. It can be seen from the results that a higher prediction accuracy can be obtained when a smaller calculation step is used. According to the test range that the high-speed camera can cover, the data acceptance rate can reach about 95%.

5. CONCLUSION

In order to quickly and accurately predict the location of the explosion point, this paper mainly focuses on non-extended range projectiles such as forced bombs and grenades, and takes the drop point test of a certain type of projectile as an example. The test equipment mainly includes initial velocity, ballistic radar, ground weather, and drop point measurement. Based on the real-time test data of the gun position, according to the first indicator projectile, the equivalent ballistic coefficient is obtained by using the external ballistic simulation method, and the ballistic model is established. After the projectile fired, the initial segment ballistic provided in real time by the ballistic radar is used. The speed is corrected twice by the data to complete the fast and accurate prediction of the impact point of the projectile.

The experimental results showed that the entire forecast time can be controlled within 8 seconds, and the equipment in the bomb drop area can complete corresponding actions according to the forecast data, which achieves the purpose of rapid forecasting of the impact point, and solves the problem that the equipment in the drop area is out of the field of view; at the same time, The model is relatively simple, has fast solution speed, and has strong real-time performance. Combined with shooting range communication, it has good application prospects:

(1) In the test of the characteristic quantities of the ballistic end such as the explosion point and the warehouse opening point, the prediction value quickly provided by this method can provide a direction for adjusting the field of view of the explosion point measurement equipment, infrared ballistic camera, etc. It is possible to test dynamic parameters such as angle of attack, falling speed, and fragmentation speed after explosion.

(2) During the demonstration of the field of view of the equipment, if the measurement equipment in the drop zone can design a follow-up device according to the predicted value, the field of view requirement can be reduced, thereby playing an advantage in increasing the resolution and improving the operating distance.

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