EFFICIENT, ACCURATE WEAPON SCORING AGAINST MOBILE THREATS IN THE REAL-TIME SIMULATED COMBAT ENVIRONMENT

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ABSTRACT

With the advent of real-time interactive combat simulation on the Advanced Simulator for Pilot Training (ASPT), a requirement for determining weapon effectiveness against moving threats was established. Traditional methods either required an excessive amount of computer memory or were restricted to low fidelity approximations. An innovative approach to this problem was developed for ASPT. An iterative approach utilizing both an aerodynamic model, based upon the weapon ballistics, and the threat position time history serves as a framework for this method. An exact determination of weapon impact or miss can be made through the use of kinetics and calculus. This method allows real-time interactive scenarios that include evasive maneuvers and ECM tactics, yet requires very little computer memory and execution time. This capability is essential for effective and realistic combat simulation.

INTRODUCTION

Background

Flight simulators are being used more and more to train pilots in weapons delivery both on the conventional range and in the hostile environment. A means of scoring the weapon projectile is essential in order to evaluate pilot performance. If the target is fixed on the terrain, scoring is relatively simple. When the bomb or bullet is released, the flight path and point of impact with the terrain can be determined, and a miss distance can be obtained that is independent of time. However, when the target is moving, real-time scoring becomes much more difficult. A time history of the target and the weapon projectile is needed so that the distance between projectile and target may be evaluated as a function of time. Depending upon the fidelity of the model used to create this time history, massive amounts of computer memory and execution time may be required.

The most common method currently in use involves updating the weapon projectile position on each iteration. This method is very accurate but requires a large amount of computer memory and execution time, especially when the weapon is a stream of cannon shells, because each round must be updated on every iteration. Even when the weapon and target position are known for each iteration, interpolation must be used to find the position between iterations. This interpolation and the techniques used for scoring the time histories of the weapon projectile and target require still more computer memory and execution time.

Statement of Problem

In a real-time, high fidelity threat environment, computer memory and execution time are at a premium. Yet, in this same environment, an accurate weapon scoring algorithm is essential. The ability to determine weapon effectiveness against stationary and mobile targets is a requirement if aircrew training or survivability are to be evaluated. Scoring against stationary targets is a straight forward evaluation of weapon ballistics. The problem of weapon scoring against mobile targets is one of finding an accurate method that requires very little computer memory or execution time. An innovative approach to the problem of mobile target scoring has been developed for use on the Advanced Simulator for Pilot Training (ASPT).

METHOD

Scoring constitutes a measurement of the distance from the target to the weapon projectile. The ASPT weapon, whether it is a bullet or a missile, is treated as a point in space located at the front edge of the projectile, and the target is treated as a sphere whose diameter is approximately the wingspan of the target (or other appropriate cross-sectional dimension depending upon the object) with the center of the sphere located at the target center of gravity. Consequently, the issue is whether the weapon (point) penetrates the target (sphere). At the present time, ASPT does not require fidelity to the degree of determining exactly where the weapon strikes the target. However, this could be found by applying the target Euler angles (roll, pitch, yaw) to the target sphere and redefining the sphere as a three-dimensional object that has the same size and shape as the target.

Scoring Algorithm

The method for ASPT mobile target scoring determines whether the target sphere is penetrated by the weapon. The calculations involved determine the exact time the weapon projectile is closest to the target and the distance between them at that time. These calculations are the same regardless of the weapon that is used.

The distance between the weapon and the target at any given time can be found by subtracting the target position from the bullet position. These positions and the difference are treated as vectors in three-dimensional space.

Equation #1: $\overline{D} = \overline{P}_{weap} - \overline{P}_{targ}$

$\overline{D}$ is distance

$\overline{P}_{weap}$ is weapon position

$\overline{P}_{targ}$ is target positon

The weapon and target position at any time can be found using Equation #2. This equation assumes a constant velocity, an assumption that will be discussed in more detail later.

Equation #2: $\overline{P} = \overline{P}_0 + \overline{V}T$

$\overline{P}$ is position at time T

$\overline{P}_0$ is position at time T = 0

$\overline{V}$ is velocity

T is time

Substituting Equation #1 into Equation #2 and expressing in terms of the coordinates of three-dimensional space yields:

Equation #3a:

$$D_x = (P_{ox} + V_xT)_{weap} - (P_{ox} + V_xT)_{targ}$$

Equation #3b:

$$D_y = (P_{oy} + V_yT)_{weap} - (P_{oy} + V_yT)_{targ}$$

Equation #3c:

$$D_z = (P_{oz} + V_zT)_{weap} - (P_{oz} + V_zT)_{targ}$$

The total distance can be found by applying the theorem that states the magnitude of a vector squared is equal to the sum of the components squared.

Equation #4: $D^2 = D_x^2 + D_y^2 + D_z^2$

Before substituting Equation #3 into Equation #4, it would be helpful to rewrite Equation #3 as follows:

$$D_x = (P_{ox_{weap}} - P_{ox_{targ}}) + (V_{x_{weap}} - V_{x_{targ}})\ T$$

$$D_y = (P_{oy_{weap}} - P_{oy_{targ}}) + (V_{y_{weap}} - V_{y_{targ}})\ T$$

$$D_z = (P_{oz_{weap}} - P_{oz_{targ}}) + (V_{z_{weap}} - V_{z_{targ}})\ T$$

Now let:

$$P_{ox} = (P_{ox_{weap}} - P_{ox_{targ}}), \quad V_x = (V_{x_{weap}} - V_{x_{targ}})$$

$$P_{oy} = (P_{oy_{weap}} - P_{oy_{targ}}), \quad V_y = (V_{y_{weap}} - V_{y_{targ}})$$

$$P_{oz} = (P_{oz_{weap}} - P_{oz_{targ}}), \quad V_z = (V_{z_{weap}} - V_{z_{targ}})$$

With these substitutions, Equation #3 becomes:

Equation #5a: $D_x = P_{ox} + V_xT$

Equation #5b: $D_y = P_{oy} + V_yT$

Equation #5c: $D_z + P_{oz} + V_zT$

Combining Equation #5 and Equation #4 gives:

Equation #6:
$$D^2 = (P_{ox}^2 + P_{oy}^2 + P_{oz}^2) + (2T)\ (P_{ox}\ V_x + P_{oy}\ V_y + P_{oz}\ V_z) + (V_x^2 + V_y^2 + V_z^2)\ (T^2)$$

This is a second order equation in time whose first derivative, when set equal to zero, will give a point of minimum or maximum. The equation for the first derivative is as follows:

Equation #7:

$$2\ (P_{ox}\ V_x + P_{oy}\ V_y + P_{oz}\ V_z) + 2\ (V_x^2 + V_y^2 + V_z^2)\ T = 0$$

Whether the point is a minimum or maximum can be determined by looking at the sign of the coefficient of the T term. This is always a positive number so the point will be a minimum. By solving for T, the time when the distance will be smallest can be found.

Equation #8:

$$T = \frac{-\ (P_{ox}\ V_x + P_{oy}\ V_y + P_{oz}\ V_z)}{(V_x^2 + V_y^2 + V_z^2)}$$

Taking the time found in Equation #8 and substituting it into Equation #6 gives the miss distance, the closest the weapon ever gets to the target. These equations are based on the assumption that the target and weapon projectile are under no acceleration. This assumption is obviously not valid for all time; however, for a very short time period, it can be considered valid. In the next section, this assumption as it applies to the target will be investigated. Following that discussion, the gun and missile applications will be reviewed and particular characteristics of these systems addressed.

Target

A no-acceleration assumption is valid when a sufficiently short time period is used. For a time period to be "sufficiently short," it must be short enough so that any normal acceleration the target would undergo could not have a significant effect on the location of the target at the end of that time period. Table 1, found in the Appendix, shows the effects of airspeed and G-loadings (acceleration) on target displacement for varying time periods.

Taking one line from Table 1 as an example, enter the table with 500 knots true airspeed (KTAS). At this airspeed, we will assume the aircraft is limited to approximately 7 Gs by either structural limits or aerodynamic stall. Using a value of 7 Gs and choosing a time period of one-tenth of a second, the lateral displacement is 1.126 feet. That means the difference between where the target would be located if it were accelerated for one-tenth of a second, and where it would be if it were not accelerated for one-tenth of a second is 1.126 feet. (See figure 1.)

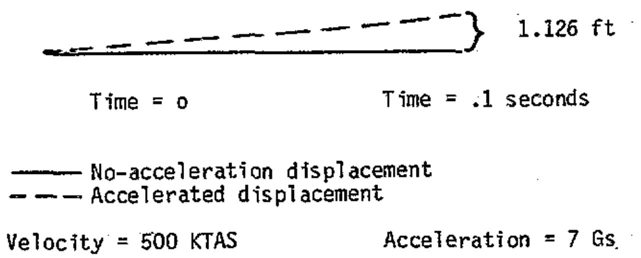

FIGURE 1 TARGET DISPLACEMENT

Based on the data in Table 1, a time period of one-tenth of a second is adequate as the boundary on a zero-acceleration assumption. Before the scoring algorithm is used, it must be determined when the weapon is within one-tenth of a second of time of impact or closest miss. Also, it must be determined if one-tenth of a second is a short enough time period for the no acceleration assumption on the weapon projectile. ASPT uses two methods at this point. Each method used is based upon the weapon involved, i.e., gun or missile.

Gun

Scoring with the gun must take into account *the fact that a large number of bullets can be* fired, each with the potential to hit the target. Evaluating each bullet individually on every iteration would require massive amounts of computation time; or storing the plotted flight path of each bullet would require a large memory capacity.

ASPT uses an innovative approach to this problem. As the bullet is fired, a bullet time of flight until impact, based on the range to the target, is determined. This time of flight is used to predict a new target position at that time of predicted impact by using existing target position, velocity, and acceleration. The new target position is used to calculate a new range, and the process is repeated. This iterative process provides an accurate, predicted impact point. Based upon the predicted range, a *predicted time of flight until bullet impact* is found. Using this time of flight and equations that model the bullet flight characteristics, bullet position and velocity for the predicted impact are found. These values (time of flight, Pox, Poy, Poz, Vx, Vy, Vz) are stored as a row in an array. If the predicted range is greater than the effective range of the gun, it is assumed the bullet will miss, and no data is stored in the array. It is interesting to note that any form of ballistic model may be used as long as bullet position and velocity can be determined at the predicted impact point. Another interesting point is that the rate of fire on most aircraft cannons is greater than most simulation iteration rates. For example, the A-10 30 mm cannon fires at 70 rounds per second and the F-16 20 mm cannon fires at 100 rounds per second. Therefore, it must be assumed that each bullet value that is stored is not one bullet but actually a stream of bullets. The values stored are the values for the midpoint in the stream.

One of the data values stored is time of flight. This time of flight is used to determine when to apply the scoring algorithm. One iteration's worth of time (based upon the simulation used) is subtracted from the time of flight value on each iteration. The time of flight remaining is then checked to see if it is within one half of an iteration of zero. When the time elapses to within one half of an iteration of zero, that row of the array is evaluated. By using the stored bullet position and velocity and the actual target position and velocity in the scoring algorithm, a miss distance can be determined.

The scoring algorithm is based upon knowing the weapon's and target's position and velocity at the same point in time. But, it is unlikely the time of flight would be an exact multiple of the iteration rate (causing time of flight to subtract to exactly zero). This means the weapon's and target's position and velocity values are probably not for the same point in time. However, the time difference would be small, less than one half of an iteration. This dilemma can be resolved by referring back to the assumption about the bullets being a stream. The velocity at any position along that stream can be considered constant for a short time period. Therefore, the bullet position and velocity values can be assumed to be valid at the time used to determine the target position and velocity. (See figure 2.)

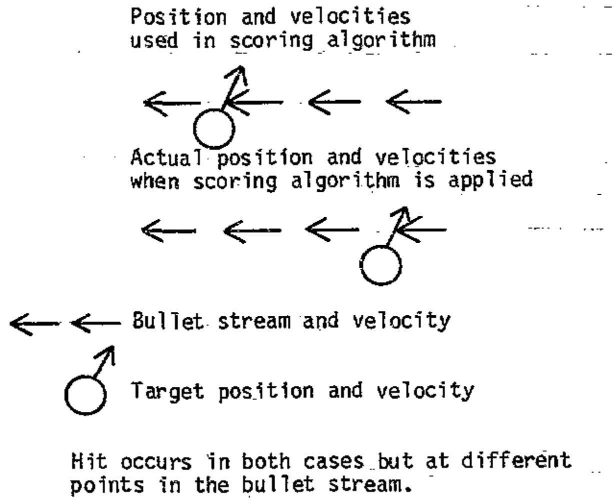

FIGURE 2 BULLET AND TARGET POSITION AT IMPACT

After a row of the array has been evaluated, it is zeroed out and not checked again unless it is reused with the values for a new bullet. By using this method, only the bullets that were predicted to hit the target on a given iteration will be evaluated on that iteration. Therefore, each bullet does not need to be evaluated on each iteration; however more than one bullet may be evaluated on a particular iteration.

The ballistic equations that account for bullet flight need only be evaluated once for each bullet. These equations are run at the time of firing, and they provide the position and velocity values at the predicted impact. Massive memory is not required since bullet position and velocity are saved for only one instant of time. The memory required on ASPT is a local array 60 X 7 in size (32 bit words). The "60" dimension is based upon ASPT's 30 Hertz (Hz) iteration rate and the fact that the maximum effective range of the bullet is always reached within two seconds; therefore, only 60 rows would be needed at any one time. Also, this method should ensure the bullet is within one-tenth of a second of impact on the target. Since the maximum time of flight for the bullets is two seconds, (based upon effective range at the gun) it is impossible for a target to maneuver in such a way that it could pass through the bullet flight path with a potential for being hit without being quite close to the predicted impact point. (See figure 3).

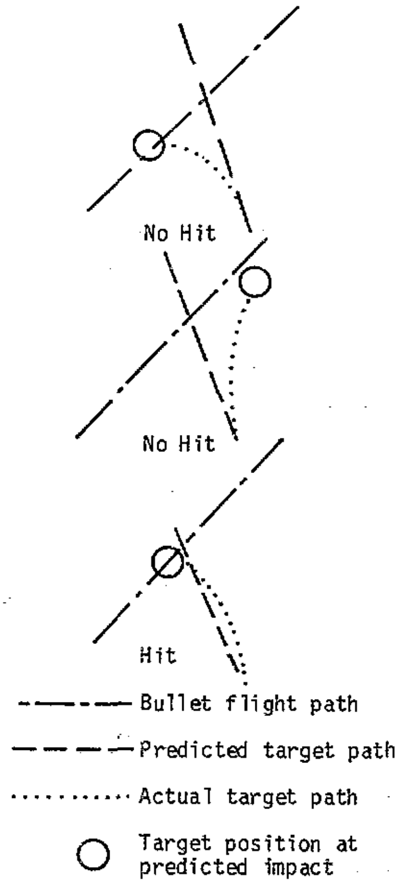

FIGURE 3 POSSIBLE BULLET AND TARGET POSITIONS

Now that the time to apply the scoring algorithm has been determined, the question remains how short a time period (based upon bullet ballistics) is required for the no acceleration assumption to be valid.

There are two primary forces which cause accelerations that affect a bullet's flight path. The first force is gravity, which acts perpendicular to the earth's surface. Over a short time period (one-tenth of a second), the gravity effect can be disregarded. The second force is supersonic drag, which acts parallel to the bullet flight path. Table 2 in the Appendix, shows the effects of drag on bullet displacement and velocity over a 1.5 second time period.

Using the .5 sec line from Table 2 as an example, we find that at .5 seconds, bullet velocity is 3140 ft/sec. The distance the bullet has traveled when using ballistic equations that account for drag is 1725 feet. If no acceleration had been assumed during the previous one-tenth of a second, the distance traveled would be 1734 feet. The difference of nine feet is not significant if we remember that the bullet is actually a stream of bullets extending in front of and behind the bullet point (See figure 2). Therefore, when the weapon used is a gun, the one-tenth of a second time period is short enough to assume no acceleration based upon the data in Table 2.

The last point to be addressed in this section is how the one-tenth of a second time period is used when applying the scoring algorithm. Recall that the scoring algorithm is applied when the time of flight to the predicted impact point has been reduced to zero. When the scoring algorithm is applied, the first thing found is the time when the minimum miss distance will occur. This time is limited to an absolute value of one-tenth of a second, the time period for the no-acceleration assumption. This means the bullet must penetrate the target sphere within one-tenth of a second from the time of the predicted impact if it is to be recorded as a hit.

Missile

A missile presents a slightly different problem. Since the missile is often fired at long range, the target aircraft will have time to perform some maneuver that will cause it to be significantly displaced from its predicted position. Also, because of its maneuvering capability, the missile's flight path is unknown ahead of time. However, only a few missiles can be active at one time, so on ASPT, each missile can be updated on every iteration without requiring excessive execution time and memory capacity.

Since both the missile and target are maneuvering, it is impossible to set a predetermined time to evaluate the miss distance. Therefore, a different technique is used. The range between missile and target is determined for each iteration. Once the missile has reached its maximum velocity, if the range between successive iterations decreases, the missile will be allowed to continue tracking the target. As soon as the range increases, it is assumed the missile just passed the target. Therefore, on the first iteration that shows an increase in range, the scoring algorithm is applied using current target and missile positions and velocities. The scoring algorithm then becomes the method used to interpolate between target and missile positions on the current iteration and the preceding iteration. ASPT runs on a 30 Hz iteration rate, therefore, the maximum time period that no acceleration is assumed is one-thirtieth of a second (one iteration). This time is well within the one-tenth of a second time period that was established for the target. The only possible problem with the no-acceleration assumption on the scoring algorithm would be the missile's own maneuvering capability. Table 3, in the Appendix, shows the effects of airspeed and G-loadings on missile displacement for a one-thirtieth of a second time period. Even for the worst case of a missile traveling 2000 knots with the capability to pull 30 Gs, the displacement due to acceleration over one-thirtieth of a second is only .536 feet. Based on Table 3, the no-acceleration assumption is valid for the missile when the time period is one-thirtieth of a second or less. The procedure for a missile, then, is to update both the target and missile positions on every iteration. When the missile stops converging on the target and first shows an increase in range, the scoring algorithm is applied using current values of position and velocity. The maximum time for the no-acceleration assumption then becomes one thirtieth of a second.

CONCLUSION

The ASPT method of scoring against a movable target allows real-time scoring using actual target and weapon positions. This method requires a minimal amount of computer memory and execution time while producing a high fidelity means of determining weapon effectiveness against mobile targets.

APPENDIX A

DISPLACEMENT TABLES

TABLE 1
TARGET DISPLACEMENT FOR VARIOUS TIMES

Airspeed (Knots)	Acceleration (Gs)	Time Period (Sec)	Displacement (Feet)
300	5	.05	.201
300	5	.10	.804
300	5	.15	1.809
500	7	.05	.282
500	7	.10	1.126
500	7	.15	2.534
700	9	.05	.362
700	9	.10	1.448
700	9	.15	3.257
900	11	.05	.442
900	11	.10	1.769
900	11	.15	3.981

Displacement is measured in feet. It is the lateral difference between where the zero-acceleration velocity vector would put the aircraft during the time period, and where the accelerated velocity vector would put the aircraft during the same time period.

TABLE 2
BULLET DISPLACEMENT AND VELOCITY

Time of Flight (Sec)	Velocity (Ft/Sec)	Distance Traveled With Acceleration (Feet)	Distance Traveled Without Acceleration (Feet)
0	3806*	0	0
.1	3678	373.2	380.6
.2	3542	731.2	741.0
.3	3404	1076	1085
.4	3270	1407	1416
.5	3140	1725	1734
.6	3014	2030	2039
.7	2894	2323	2331
.8	2777	2604	2612
.9	2664	2874	2882
1.0	2555	3133	3140
1.1	2450	3381	3389
1.2	2347	3619	3626
1.3	2248	3846	3854
1.4	2152	4064	4071
1.5	2058	4273	4279

*Muzzle velocity plus true airspeed.

This data is based upon the F-16 20MM cannon; the data is valid for an aircraft at 10,000 MSL and 300 KTAS. The maximum effective range of this gun is 4000 feet. The "Distance Traveled Without Acceleration" column is based upon no acceleration during the previous one-tenth of a second, not for the entire time of flight.

TABLE 3
MISSILE DISPLACEMENT
DURING ONE THIRTIETH OF A SECOND

Airspeed (Knots)	Acceleration (Gs)	Displacement (Feet)
500	15	.268
500	20	.357
500	25	.447
500	30	.536
1000	15	.268
1000	20	.357
1000	25	.447
1000	30	.536
1500	15	.268
1500	20	.357
1500	25	.447
1500	30	.536
2000	15	.268
2000	20	.357
2000	25	.447
2000	30	.536

Displacement is measured in feet. It is the lateral difference between where the zero-acceleration velocity vector would put the missile during the time period, and where the accelerated velocity vector would put the missile during the time period.

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