A method of directing the firing of a gun and a system for its implementation. A final gun-fire order, aim correction, is deduced analytically based on observed performance, for example the miss distance of at least one previously fired projectile. Both the correlated and uncorrelated aspects as well as the bias of the observed performance are accounted for by assuming that the correlated aspects may be represented as a Markov process. A Kalman filter, linear predictor, and a storage-feedback device can then be employed to derive a correction order which may be applied to a subsequently fired projectile, thus minimizing the mean square miss distance.
CLOSED-LOOP GUN CONTROL SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates generally to closed-loop fire control systems for projectile launchers and more particularly to a closed-loop gun control system and method of operation for directing the firing of projectiles at a stationary or moving target.

Closed-loop control is not a new concept for gunnery. In anti-aircraft missions, tracer bullets or projectile bursts provide a visual indication of miss distance, which the gunner then uses to correct his gun positioning. Likewise, in naval shore bombardment, a forward observer notes the fall-of-shot and calls back an aim correction. A closed-loop system is simply characterized by first observing the gun’s performance and then deriving a best correction or feedback term based on those observations.

Therefore, there are two key elements involved in closed-loop systems—measuring gun performance and the derivation of a best correction or feedback term. Performance may be characterized by measurements of miss distance, actual muzzle velocity, or combinations thereof. Historically, miss distances have been deduced by a spotter. However, spotter measurements suffer from inaccuracy; and, as firing rates increased, the evaluation of every projectile fired became impossible for the individual spotter. Advances in radar systems have solved this problem, and miss distances as well as other system performance parameters can now be measured accurately, even in the case of rapid-fire weapons. Miss distance may be defined as the distance between the projected impact point and the closest point of approach of the projectile to that impact point.

On the other hand, the second element of closed-loop operation—deriving a best correction or feedback term—has heretofore eluded satisfactory solution. Designs of previous systems and methods are based on inadequate statistical representations of performance; thus the best possible correction is not provided. Typically, an observer estimates miss distances for a predetermined number of rounds, and determines the average miss for use as a correction order. Radar systems measure both miss distance and muzzle velocity; and corrections are based on an averaging technique.

The problem is that these systems of correction determination are based on an incomplete gun-system error model, i.e., the error model assumes that the stochastic (or random) component of the miss distance or muzzle velocity is uncorrelated. These errors are actually composed of two components. The first is called system bias, which may, for example, be caused by boresight error, and can be corrected for by feeding back the mean or average impact point after each round is observed. This mean or average impact point, called the bias point, is, in general, a vector quantity whose components, for instance, might be average miss distance in range, elevation, and azimuth at warhead detonation.

The second error component is called the stochastic (or random) component and results in dispersion about the bias point. Previous correction systems, as noted above, have treated this stochastic component as a totally uncorrelated process and simply generated corrections based on an average of all observed miss distances. However, firing data has shown that the stochastic component does, in fact, have a statistically correlated aspect. The term correlated, as employed herein, is used to describe the phenomenon of statistical dependence of the miss distances between rounds. From this dependence one may estimate the stochastic component of the error of one shell based on the measurement of previous errors. It might be of further assistance in the understanding of these concepts to observe that the component of the miss distance among individual projectiles due, for instance, to their variability in aerodynamic characteristics would be considered uncorrelated, while the correlated aspect could represent such systematic and time dependent effects as inertial lag and servo hunt. By not taking into account the correlated aspect of the stochastic component, previous systems and methods failed to achieve the best correction term possible.

SUMMARY OF THE INVENTION

By accounting for the constant character of the bias and the correlation of the stochastic component of the error, the instant invention overcomes the deficiencies of previous systems. This result is accomplished by employing a recursive filter in the gun fire control system. The filter may simply be added to an old system, replace an existing filter in an old system, or be an integral part of a new system. The filter receives performance data (e.g., miss-distance and muzzle velocity) from a measuring device, and provides corrections which reflect the constant bias and the correlated aspect of the stochastic component of the error. These corrections are then used to modify the gun order that the system into which the filter has been incorporated would have produced.

An object of the present invention is to account for both the bias and correlated aspects of the error in determining gun-control correction orders.

A further object of the invention is to provide a recursive filter for use in a gun control system.

Another object is to estimate future misses using previous miss data by employing a linear predictor.

Other objects, advantages, and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of an embodiment of the invention;
FIG. 2 is a representation in block form of the miss distance components;
FIG. 3 is a representation in block form of the recursive filter;
FIGS. 4a-c are illustrations of the filter and control device shown in FIG. 1; and
FIGS. 5a-c are schematics of a digital embodiment of the filter and control illustrated in FIG. 4

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1, which illustrates a preferred embodiment of the gun-control system, shows a radar device 10 for measuring target position. A velocity derivation unit 12 receives input from the radar 10 and, from sequential measurements of position, estimates target velocity. An
impact point prediction unit 14 employs the estimated target velocity and stored ballistic data to compute an impact point. The predicted impact point is then transmitted to unit 16 which determines gun-control orders and activates various motors (not shown) on the gun to aim it and thereby attempt to hit the projected impact point with the shell next to be fired. However, various factors (e.g., boresight error) in the gun process will generally cause the shell to miss the projected impact point.

The system described to this point is well known. Units 12, 14 and 16 could, for example, be a properly programmed, general purpose, digital computer. The process described would be repeated each time a round is fired, and firing would continue until it has been determined that the target is destroyed or it is no longer within gun range.

In addition to the above described devices, previous systems have also employed miss distance or muzzle velocity measuring units. A unit for measuring miss distance is schematically represented by block 18 in FIG. 1. The miss distance measured will be a vector quantity whose components, for instance, might be miss distance in range, elevation and azimuth. This miss distance is then used to determine a correction which is applied to the gun order. Similarly, muzzle velocity measurements could also be employed. Heretofore, the correction was simply an average of previous miss distances or muzzle velocities and therefore did not account for the correlated aspect of the error.

The present invention, based on a gun-system error model which consists of the correlated, uncorrelated and bias errors, employs a recursive filter to derive a best correction. Such a filter is represented by block 20 in FIG. 1 and is connected to a control unit 22, which governs its sequence of operations.

As described above, error models previously used to derive gun order corrections consisted only of a bias and uncorrelated stochastic component. However, test data has shown the stochastic component to consist of both an uncorrelated and a correlated portion. Therefore, the problem is, given error measurements, to determine a correction term that accounts for not only these two and the uncorrelated stochastic errors but the correlated stochastic portion as well. The present invention derives corrections based on an error model which includes all three errors—something which other systems have failed to do.

To illustrate an embodiment of the invention, an application to correct for miss distance will be given. The miss distance of the nth projectile in the X and Y directions, for instance, azimuth and elevation, may be represented by

$$X_n = \alpha_n + b + \beta_n$$

(2)

The correlated aspect of the stochastic component of the miss distance, viz., $\alpha$, is modeled as a Markov process. Although higher order Markov processes may be appropriate in other instances, in this illustration $\alpha_n$ will be taken as first order and may be expressed as follows:

$$\alpha_n = \rho \alpha_{n-1} + (1 - \rho^2)^{1/2} \theta_n$$

(3)

where: $\alpha_1 = \theta_1$

By representing the correlated portion of the stochastic component of miss distance as a Markov process, one can apply a recursive filter to determine the best correction term, that is, one can obtain a correction term that minimizes mean square error.

In equation (3) $\rho$ is the correlation coefficient of the Markov process. $\theta_n, n=1, \ldots$ is a statistically orthogonal error sequence, with mean zero and variance $\sigma^2 = \rho^2$ that is letting $E[U]$ denote the statistical average of $U$, $\theta_n$ is defined by the following properties:

$$E[\theta_n^2] = \sigma^2$$

(4)

$$E[\theta_n \theta_m] = 0 \text{ for all } n \neq m$$

Similarly $\beta_n, n=1, \ldots$ in equation (2) is an error sequence with the following properties:

$$E[\beta_n^2] = \sigma^2 \text{ for all } n$$

(5)

$$E[\beta_n \beta_m] = 0 \text{ for all } n \neq m$$

$$E[\beta_n \beta_m] = 0 \text{ for all } n \neq m$$

(6)

where the last property denotes the statistical orthogonality of the $\beta$-error and $\beta$-error sequences. The correlation coefficient $\rho$ in equation (3) and the variances $\sigma^2$, $\delta^2$ and $\Delta^2$ are performance characteristics of the system and can be determined, for instance, as disclosed by J. Bram in "Estimation of Aim-Error Correlation, Aiming Dispersion, and Ballistic Dispersion," Research Contribution 202, Center for Naval Analyses, Arlington, Va. (1972).

Given the above as an error model, the problem is to use previous miss data to estimate future misses. These estimates will then be used to generate corrections to the gun order to reduce future miss distances; more specifically, they will be subtracted from the gun order. This process of estimation is illustrated with reference
to the filter 20 in FIG. 3. First, the actual miss distance \( X_n^- \) of a previously fired shell is measured. This miss distance \( X_n^- \) will be a function of the correlated component \( \alpha_n \), the bias \( e \), and the uncorrelated component \( \beta_n \). However, because a correction order \( X_n^- \) was subtracted from the gun order for this previously fired shell, the measured miss distance \( X_n^- \) will be a function of that previous correction order. Thus \( X_n^- \) can be added to the measured miss distance \( X_n^- \) to derive \( X_n \), the miss distance solely as a function of the \( \alpha \) and \( \beta \) processes and system bias \( b \) as described in reference to equation (2).

\( X_n \), the actual miss distance which would have occurred without application of the previous correction order \( X_n^- \) now serves as input for an optimal estimator consisting of a Kalman filter 30 connected to a linear predictor 28. The optimal estimator derives a correction \( \hat{X}_{n+2} \) to be applied to the next round to be fired, where \( p \) represents the number of shells in the air between the gun and the target including the one for which the miss distance \( X_n^- \) has just been measured. \( \hat{X}_{n+2} \) is not only employed as a correction but is also stored in the storage-feedback device 26 for application to the eventual miss distance measurement of the round about to be fired, that is \( X_{n+p}^- \).

The problem, using the above symbols, can now be expressed as attempting to find \( \hat{X}_{n+2} \), where \( \hat{X}_{n+2} \) is the best estimate (in the minimum mean square error sense) of \( X_{n+2} \) (the actual miss distance, as a function of the \( \alpha \) and \( \beta \) processes and system bias \( b \)) of the round about to be fired, given the previous measurements of the miss distance \( X_1, \ldots, X_n \). The optimal estimator that will achieve this result is a Kalman filter followed by a linear predictor. These elements are illustrated in block form in FIG. 3 as 30 and 28 respectively. This result, originally presented by Kalman in his article "A New Approach to Linear Filtering and Prediction Problems" published in Volume 82D, of the March 1960 edition of the Journal of Basic Engineering at pages 35–44, is now treated extensively in advanced texts on estimation theory. See, e.g., Meditch, J. S., Stochastic Optimal Linear Estimation and Control, McGraw-Hill, New York, 1969.

The equations that describe the filter 20 for the illustrative example can now be given as follows.

The miss distance of the \( n \)th shell \( X_n \), which is the miss distance that would have occurred if the correction term \( \hat{X} \) has not been applied, is determined as the sum of the measured miss distance \( X_n^- \) and the output \( \hat{X}_n \) of the storage-feedback device; that is

\[ X_n = X_n^- + \hat{X}_n \]  

(4)

To present the essential equations for the Kalman filter, the system of equations (2) and (3) are rewritten in the following vector form:

\[
\begin{bmatrix}
\alpha_n \\
\beta_n
\end{bmatrix} =
\begin{bmatrix}
\rho & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\alpha_{n-1} \\
\beta_{n-1}
\end{bmatrix} +
\begin{bmatrix}
(1-\rho^2)^{1/2} \\
0
\end{bmatrix}
\theta_n
\]  

(5)

\[ X_n = [1] \begin{bmatrix}
\alpha_n \\
\beta_n
\end{bmatrix} + \beta_n \]  

(6)

where the constant unknown bias has also been expressed as a difference equation. By defining \( U_n, \Phi, \Gamma \) and \( h \) as

\[ U_n = \begin{bmatrix}
\alpha_n \\
\beta_n
\end{bmatrix}, \quad \Phi = \begin{bmatrix}
\rho & 0 \\
0 & 1
\end{bmatrix}, \quad \Gamma = \begin{bmatrix}
(1-\rho^2)^{1/2} \\
0
\end{bmatrix}, \quad h = \begin{bmatrix}
1
\end{bmatrix} \]

(7)

the equations (5) and (6) are rewritten as

\[ U_n = \Phi U_{n-1} + \Gamma \theta_n \]

(8)

where \( h' \) is the transpose of the vector \( h \). Thus, in terms of the foregoing defined quantities, the necessary equations that define the Kalman filter 30 for equations (7) and (8) are as follows:

\[ \hat{U}_n = \Phi \hat{U}_{n-1} + S_n [X_n - h' \Phi \hat{U}_{n-1}] \]

(9)

\[ S_n = (1/\sigma h P_n h) \]

(10)

\[ P_n = R_n - R_n h' P_n h + \sigma^{1-1} h' R_n \]

(11)

\[ R_n = \Phi P_{n-1} \Phi' + \sigma \tilde{\Theta} \Gamma' \]

(12)

\[ U_i = \begin{bmatrix}
0 \\
1
\end{bmatrix} X_i, \quad P_i = \begin{bmatrix}
0 & 0 \\
0 & 0 \sigma \tilde{\Theta} + \sigma \tilde{\Theta}
\end{bmatrix} \]

(13)

The output of the linear predictor is specified by the equation

\[ \hat{X}_{n+2} = h' \Phi \hat{U}_n \]

(14)

which is the desired correction term.

The foregoing equations for the Kalman filter and linear predictor include the integer indices \( n \) and \( p \). \( i \) is the number of shells fired thus far and \( p \), the number of shells in the air, is obtained from

\[ p = i - n \]

(15)

where \( n \) is the number of miss data measurements received thus far.

FIG. 4a is a flow diagram of the Kalman filter defined by equations (9)–(13), the linear predictor defined by equation (14), and the storage-feedback device. In this illustrative example the components of the vector \( S_n \), denoted by \( A_i(n) \) and \( B_i(n) \), are precomputed and stored in tables as depicted in FIG. 4b. \( C_i(p) \), which equals \( \rho_i \), is also stored as indicated. FIG. 4c illustrates the control and interlock in block diagram form. The control provides the integer indices \( n, p \) and \( i \) as defined.
supra in reference to equation (15), and the timing interlock ensures proper sequencing of operations.

FIG. 5 depicts a digital implementation that can be incorporated as shown into a digital gun system or into an analog gun system with the addition of analog-to-digital and digital-to-analog converters. Each of the circuit elements shown in FIG. 5 are commercially available items of digital hardware. FIG. 5a is an implementation of the filter 20 and control 22 of FIG. 1. FIGS. 5b and 5c are circuit diagrams of the timing interlock shown in FIG. 5a. FIG. 5c being the circuit diagram of the gated oscillator depicted in FIG. 5b.

The method of operation of the device of FIG. 5 was described previously with reference to FIG. 3. There are some characteristics of the implementation, however, that merit further discussion.

The buffers depicted in this circuit function as time delay units and additionally serve to hold and make available previous results until new results are available. The storage-feedback unit of this invention consists of a read/write memory device. This device stores correlation terms as they are generated and makes them available for subsequent use. The timing interlock provides sequencing commands that ensure valid execution of the several steps in the method. For example, it provides read-out suppression signals to buffers to prevent read-out during the time new entries are being made.

The operation of the embodiment of the invention shown in FIG. 1 may be described as follows. Upon target acquisition a projected impact point is derived by the radar 10, velocity derivation unit 12, and impact point predictor unit 14. A gun order is then given by unit 16 and firing is commenced. Initially, particularly with a rapid-fire weapon, several projectiles may be fired before a correction order can be derived, since measurements of some performance components, for instance, miss distance, cannot be immediately determined.

At the first opportunity performance components of interest are measured, and control device 22 activates filter 20 which then derives a correction order, by estimating these performance components for the shell next to be fired. This correction will not only be applied to the gun orders for the shell next to be fired but will also be stored in the storage-feedback device 26 to be utilized when the performance components of the next to be fired shell are measured. For each subsequently fired shell a correction will be provided based on all previously measured performance components.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A system for directing the firing of a weapon at a target comprising:
- means for determining the velocity of the target;
- means for predicting an impact point for the projectile next to be fired from said velocity;
- means for deriving a gun order for aiming the weapon based on the predicted impact point;
- means for measuring at least one performance component of a previously fired projectile; and
- means for determining a correction to be applied to said gun order based on said measured performance component of said previously fired projectile,

the correction-determining means including a recursive filter connected to a linear predictor, and a storage-feedback device connected to the linear predictor and recursive filter.

2. The system of claim 1 wherein said recursive filter comprises a Kalman filter.

3. A method of aiming a weapon based on the performance components of previously fired projectiles, said method comprising the steps of:
- projecting a desired impact point for the next to be fired projectile;
- determining a gun order based on that projected impact point;
- measuring at least one performance component of a previously fired projectile;
- deriving a correction based on both the correlated and uncorrelated aspects of said performance component;
- modifying said gun order with said correction;
- employing the corrected gun order to aim the weapon;
- storing the correction;
- firing the next to be fired projectile;
- measuring the actual miss distance of the next to be fired projectile;
- determining the portion of said actual miss distance not due to the previously derived and stored correction; and
- deriving a new correction from said portion to be applied to the gun orders for a projectile about to be fired.

4. The method of claim 3 wherein the step of deriving a correction order comprises:
- estimating the performance component of the next to be fired projectile based on the following error model:

\[ X_n = a_n + b + \beta_n \]

where \( X_n \) is one of the components of performance of the \( n \)th projectile, \( b \) is the system bias, \( \beta_n \) represents the uncorrelated aspect of \( X_n \), and \( a_n \) is a process which represents the correlated aspect of the component and is taken as Markovian.

5. The method of claim 3 wherein the step of deriving a correction comprises:
- estimating the performance component of the next to be fired projectile based on the following error model:

\[ X_n = a_n + b + \beta_n \]

where \( X_n \) is one component of performance of the \( n \)th projectile; \( a_n \) is a process which represents the correlated aspect of the stochastic component of \( X_n \) and is defined by

\[ a_n = \rho a_{n-1} + (1-\rho^2)^{1/2} \theta_n \]

\[ a_1 = \theta_1 \]

where \( \rho \) is the correlation coefficient, and \( \theta_n \) is an uncorrelated error process; \( \beta_n \) is a process which represents the uncorrelated aspect of the stochastic component of \( X_n \); and \( b \) is the system bias.

6. A system for directing the firing of a weapon at a target comprising:
- means for determining the velocity of the target;
- means for predicting from said velocity an impact point for the projectile next to be fired;
means for deriving a gun order for aiming the weapon based on the predicted impact point;
means for measuring at least one performance component of a previously fired projectile; and
filter means, including a recursive filter connected to a linear predictor, for providing a correction to said gun order based on said measured performance component, said measured performance component taken as including a system bias, a correlated Markovian error, and an uncorrelated error.

7. The system of claim 6 wherein the correlated Markovian error is second order.
8. The system of claim 6 wherein the correlated Markovian error is first order.

9. A method of aiming a weapon based on the performance components of previously fired projectiles, said method comprising the steps of:
projecting a desired impact point for the next to be fired projectile;
determining a gun order based on that projected impact point;
measuring at least one performance component of at least one previously fired projectile;
estimating the bias and correlated components of the performance component of the previously fired projectile;
predicting the bias and correlated components of the performance component of the next to be fired projectile;
modifying said gun order with the predicted performance component;
employing the modified gun order to aim the weapon;
 storing the predicted performance component;
firing the next to be fired projectile;
measuring at least one actual performance component of the next to be fired projectile;
determining the portion of said actual performance component not due to the previously derived and stored predicted performance component; and
deriving a new predicted performance component to be applied to the gun orders for a projectile about to be fired.

10. The method of claim 9 wherein the correlated component of the performance component of the previously fired projectile is taken as Markovian.

11. The method of claim 10 wherein the correlated component of the performance component of the previously fired shell is taken as second order Markovian.

12. The method of claim 10 wherein the correlated component of the performance component of the previously fired shell is taken as first order Markovian.