March 9, 1954 W. W. HANSEN 2,671,613

ELECTRICAL GUN DIRECTING SYSTEM

Filed April 19, 1943 3 Sheets-Sheet 1

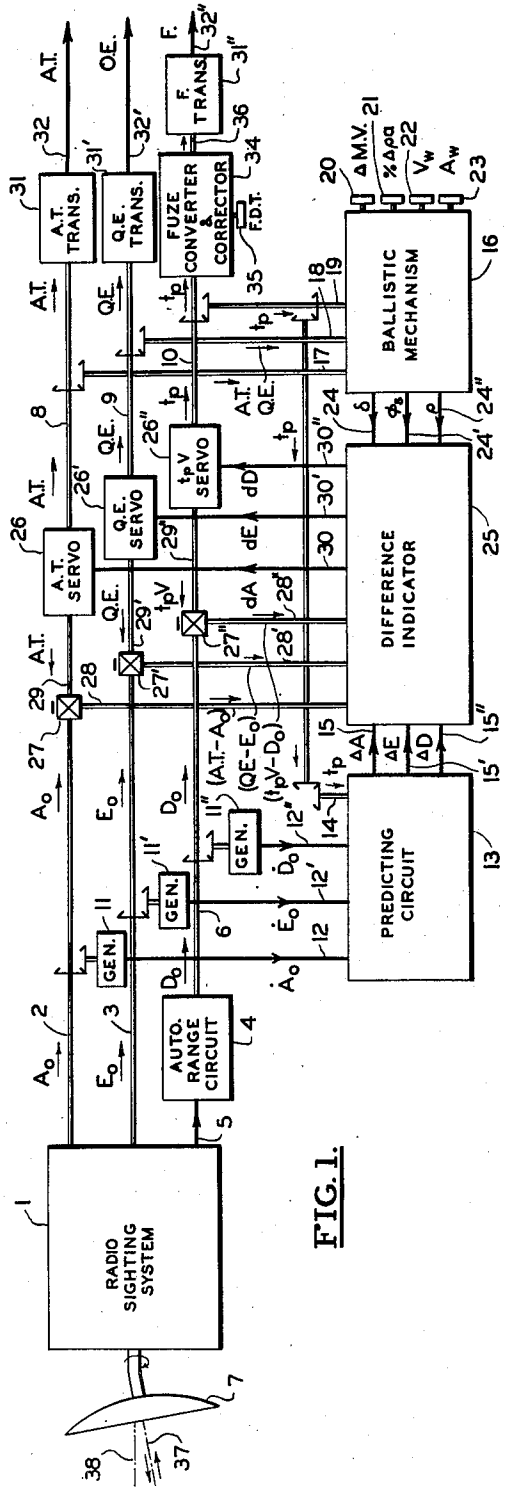

FIG. 1.

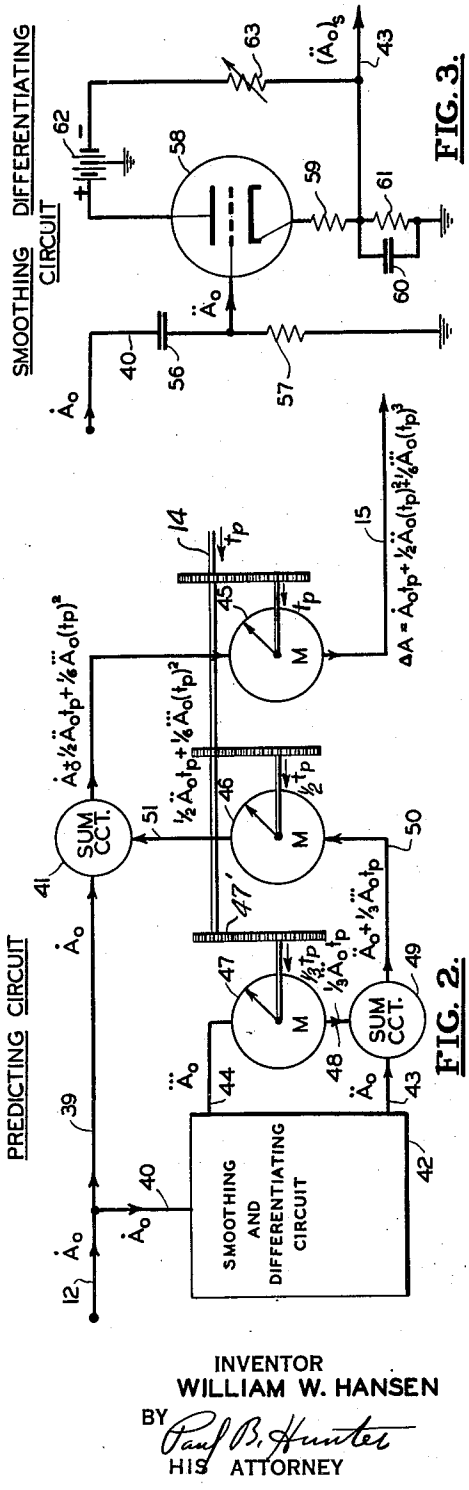

FIG. 3.

FIG. 2.

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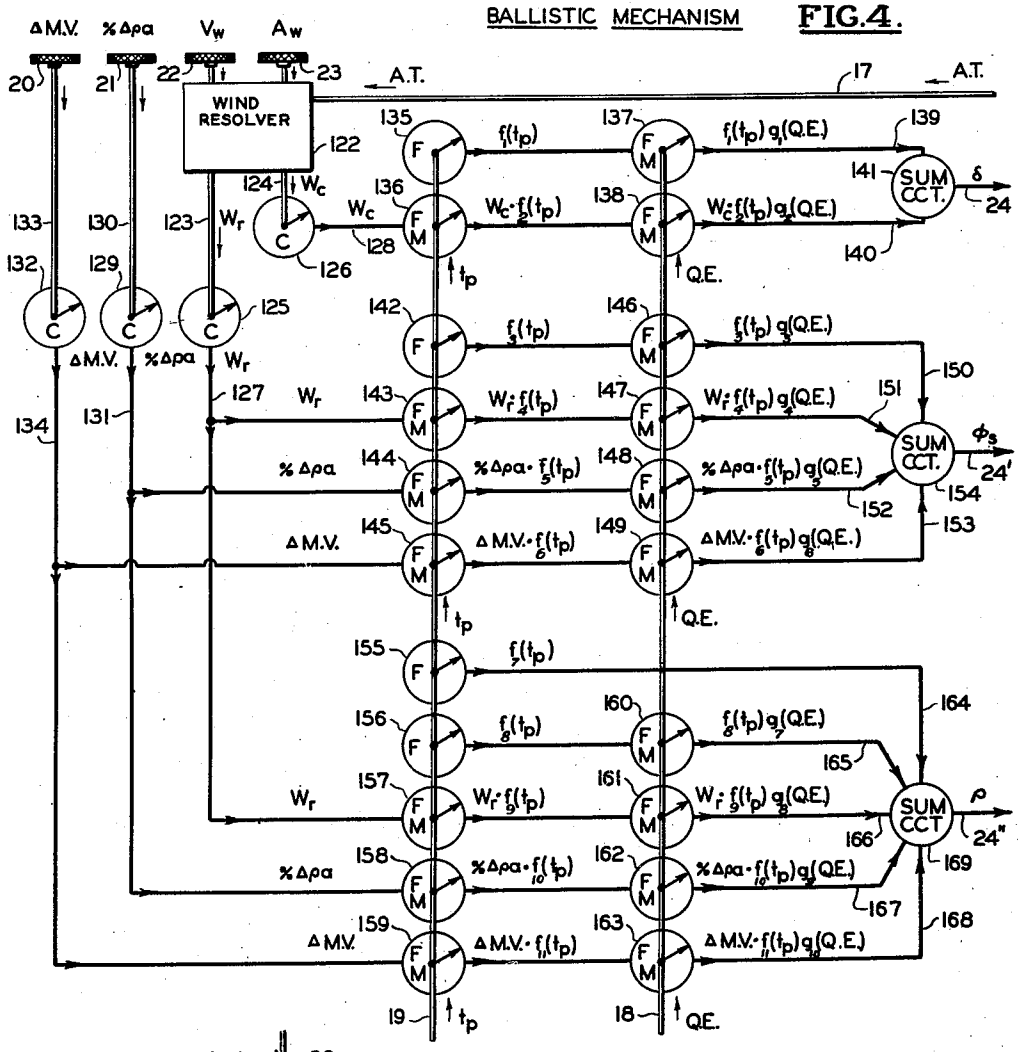
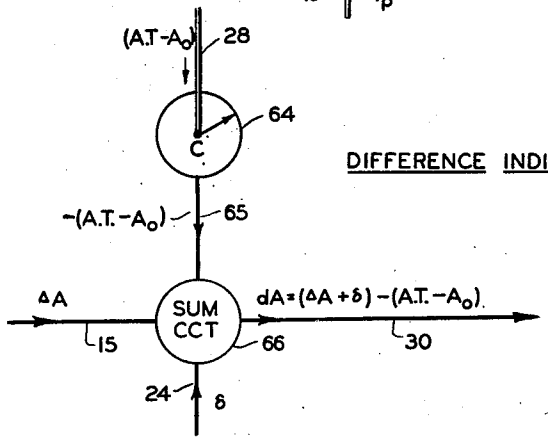
ELECTRICAL GUN DIRECTING SYSTEM

Filed April 19, 1943 3 Sheets-Sheet 2

BALLISTIC MECHANISM **FIG.4.**



DIFFERENCE INDICATOR **FIG. 5.**



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ELECTRICAL GUN DIRECTING SYSTEM

Filed April 19, 1943 3 Sheets-Sheet 3

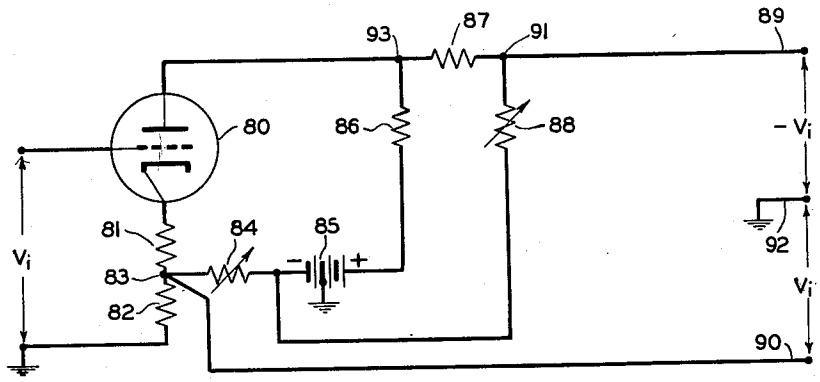

FIG. 6.

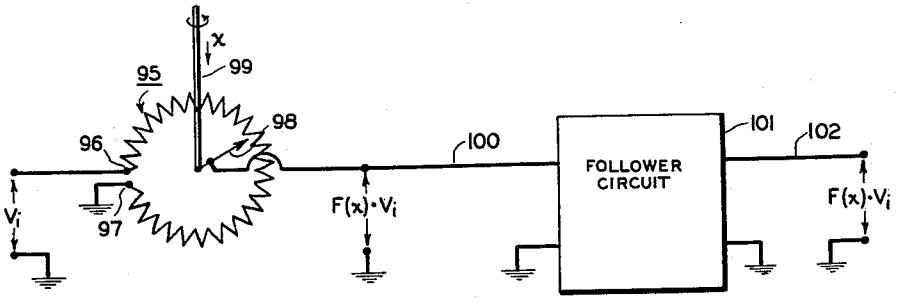

FIG. 7.

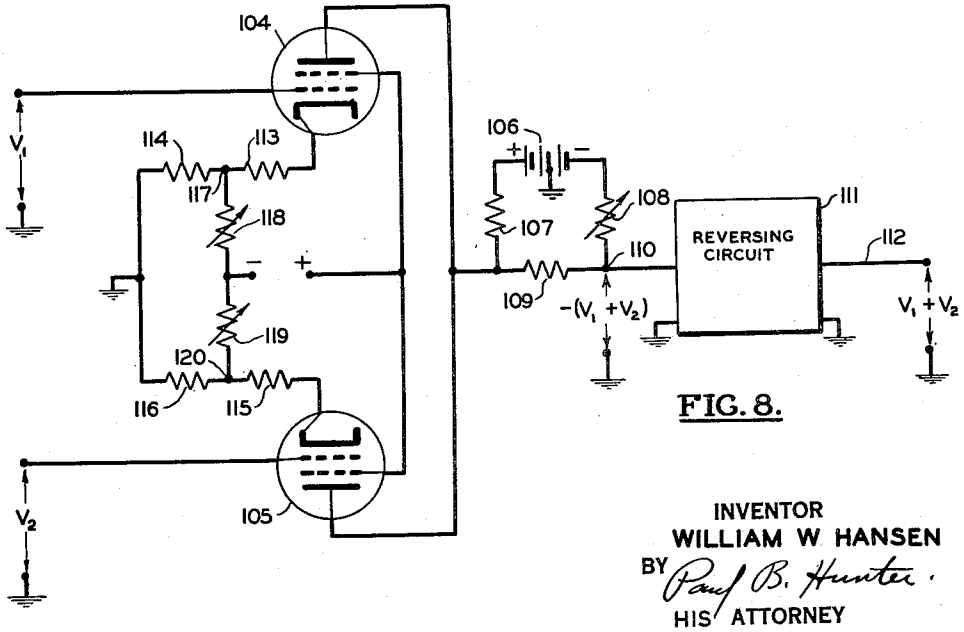

FIG. 8.

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2,671,613

ELECTRICAL GUN DIRECTING SYSTEM

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Application April 19, 1943, Serial No. 483,679

6 Claims. (Cl. 235—61.5)

1

This invention relates generally to the art of gun fire control, and more particularly, to means for, and methods of, continuously controlling the firing of guns so as to effect hits against rapidly moving targets, such as airplanes. Although primarily intended as an anti-aircraft director, the apparatus of the present invention will obviously function equally well to solve the more simple fire control problems, such as directing fire against surface craft, stationary targets, and so forth.

In presently used gun directors, such as that described in U. S. Patent No. 2,065,303 entitled "Apparatus for the Control of Gun Fire," issued December 22, 1936, in the names of E. W. Chafee, et al., are essentially mechanical devices. In such directors, electrical energy is utilized only to supply power for operation of the various mechanical components, such as cams, differentials, variable speed devices, and so forth, which devices mechanically accomplish all the various arithmetical and algebraic computations necessary for the solution of the fire control problem.

Some of the more important advantages of the electrical gun directing system herein disclosed over prior mechanical directors lie in its lightness, compactness, cheapness, and general simplicity. In order to attain the necessary accuracy in a mechanical director, low scale factors must be maintained throughout, and each element, therefore, must be comparatively large. As a result, the whole director becomes a large, heavy, and unwieldy device. On the other hand, each element of the present electrical gun director is inherently small and light, and in general, the accuracy attained in each element is not a function of its size. The complete electrical gun director may, therefore, be much smaller and lighter than an equally accurate mechanical director.

Another advantage attained in the present electrical gun director is the reduction of the "shaft and gearing" problem. In designing a mechanical gun director it becomes quite some problem to actually fit the various component parts together in a unitary structure of a reasonable size. This is due to the great number of shafts and gearing which must cooperate with other shafts and gearing without interfering with still other parts of the director. In the present gun director, since data is transmitted mainly in the form of electrical voltages rather than shaft displacements, it becomes possible to design each component separately with regard only to its particular function, and then simply connect the various components together with conducting

2

leads. Besides resulting in a more compact director, such a construction also has the advantage of being easier to service.

Also, in mechanical directors considerable difficulty is often met in insuring stable performance of the servo and follow-up devices involved. As is well known, stable operation of such devices depends essentially on having a big difference between the time constant of the various component devices and the time constant of the complete system. Since an enormous range of time constants is readily available in the electronic equivalent of mechanical servos, this difficulty is eliminated.

Another problem encountered in the design of a mechanical director is that of backlash in the gears. Since there is no electrical equivalent to backlash, this problem is also eliminated in the present electrical director.

In presently used mechanical directors the prediction of the future position of the target is carried out in rectangular coordinates, and is based upon the assumption that the target is flying in a straight line at a constant velocity. Since present target position data is necessarily received from the sighting system in spherical coordinates, it becomes necessary in these directors to convert these spherical coordinates into the corresponding present position rectangular coordinates to compute the future position of the target in rectangular coordinates, and then to convert these computed future position rectangular coordinates back into the corresponding future position spherical coordinates, which last data may then be employed for controlling the angular position of the gun and the fuze setting of the projectile.

In the present application there is disclosed an electrical gun director which accomplishes the prediction of the future target position in spherical coordinates directly without first converting to rectangular coordinates. In the past this has been thought impractical because of the difficulty involved in obtaining the many higher order time derivatives of the incoming present position data which are necessary in order to predict in spherical coordinates. In the present application this difficulty is overcome by employing electrical differentiating and smoothing circuits, which are much more accurate and practical than mechanical differentiating circuits to obtain the necessary higher derivative data. By thus predicting in spherical coordinates, the necessary double conversion from spherical coordinates to rectangular coordinates and then back again to spherical coordinates, and the re-

sulting loss of accuracy involved in this double conversion are eliminated.

As previously stated, presently used fire control directors base their prediction of the future position of the target upon the assumption that the target is flying in a straight line at a constant velocity. In the present invention, the future position computed is the true future position based, not upon any assumptions at all, but upon the true mode of motion of the target as determined by the instantaneous values of the successively higher order derivatives at the time of firing. In this way the gun director of the present invention is capable of effectively directing gun fire against a target which is flying at an accelerating rate, or in a curved path, or having any other mode of motion.

Another advantage accomplished by predicting in spherical coordinates is that it becomes possible to apply the present position spherical coordinate data received from the sighting system directly to the guns as a first approximation, and to compute in the predicting and ballistic apparatus only correction factors which may then be applied to the gun to finally position it. This avoids the necessity of carrying the major portion of the final gun position data all the way through the computing system, thus allowing the use of higher scale factors in the computing apparatus and resulting in greater accuracy in the ultimate solution.

Accordingly, an object of the present invention is to provide an electrical gun directing system.

Another object of the invention is to provide a simple, cheap, compact, and accurate gun directing system.

Another object of the invention is to provide a gun director operating wholly in spherical coordinates.

Still another object is to provide electrical fire control apparatus for computing the prediction corrections in spherical coordinates directly from the present position spherical coordinates of the target.

A further object of the invention is to provide apparatus for accurately computing the prediction corrections to be applied to a gun in order to hit a target which is traveling at an accelerated rate, or in a curved path, or according to any other mode of motion.

A still further object is to provide a gun director wherein only correction terms are involved in the computing apparatus.

Other objects and advantages will become apparent in the specification taken in connection with the accompanying drawings wherein the invention is embodied in concrete form.

In the drawings,

Fig. 1 is a schematic diagram of the complete gun directing system of the present invention.

Fig. 2 is a schematic diagram of the azimuth component of the predicting circuit of Fig. 1.

Fig. 3 is a wiring diagram of a smoothing and differentiating circuit which may be employed in connection with Fig. 2.

Fig. 4 is a detailed schematic diagram of the ballistic mechanism of Fig. 1.

Fig. 5 is a schematic wiring diagram of the azimuth component of the difference indicator of Fig. 1.

Fig. 6 is a wiring diagram of a circuit employed for various purposes in the system.

Fig. 7 is a representation of the potentiometer unit employed for multiplying and for other purposes.

Fig. 8 is a wiring diagram of the sum circuit employed for algebraically adding two voltage signals.

Similar characters of reference are used in all of the above figures to indicate corresponding parts. Arrows are used to indicate the direction of flow of information or control influences.

Referring now to Fig. 1, wherein the complete gun directing system is schematically shown, an automatic radio sighting system 1 is employed to obtain the azimuth angle (A_0) as a proportional rotation of output shaft 2, and the elevation angle (E_0) as a proportional rotation of output shaft 3, of the present position of the target, and to provide the automatic range circuit 4 with the necessary information as on output lead 5, for it to solve for and produce as a proportional rotation of shaft 6, present slant range (D_0).

Although the radio sighting system may be of any suitable type adapted to accomplish this purpose, preferably a reflected-pulse radio sighting system of the type disclosed in copending application Serial No. 441,188 for "Radio Gun Control System," filed in the names of C. G. Holschuh et al., April 30, 1942, is employed. As described in that application, periodic pulses of electromagnetic energy are radiated in a conical fashion about the target from a suitable reflector, schematically indicated at 7, which reflector has its radiation axis 37 slightly offset from its spin axis 38 as shown.

Reflector 7 is also employed to receive back corresponding pulses reflected from a target lying within the irradiated conical portion of space. The phase and magnitude of the variation in intensity of the reflected pulses is then interpreted by suitable detecting circuits which produce output signal voltages proportional to the angular deviation in elevation and azimuth of the axis of the cone of space irradicated (the spin axis of reflector 7) with respect to the line of sight of the target.

These voltage signals are then introduced into suitable servo mechanisms which reposition the spin axis of reflector 7 in such a direction as to reduce these signal voltages to zero. In this manner the spin axis is continuously maintained coincident with the line of sight to the target, thus providing a measure of the angular position of the target in elevation and azimuth. The azimuth and elevation output shafts 2 and 3 may be directly connected to the shafts which control the orientation of the spin axis so that the angular displacement of shafts 2 and 3 will be respectively proportional to the present azimuth (A_0) and present elevation (E_0) of the target.

The automatic range circuit 4 receives on lead 5 both the transmitted pulses and the corresponding reflected pulses of electromagnetic energy. As is well-known, the lapse of time between a transmitted pulse and a corresponding received pulse is proportional to the distance to the target. The automatic range circuit 4, which may be of the type disclosed in copending application Serial No. 432,290 for "A Pulse System," filed February 25, 1942 in the name of W. M. Silhavy, or any other suitable type, is adapted to measure this time interval and provide on its output shaft 6 an angular displacement proportional to this time interval, and therefore proportional to the slant range (D_0) to the target.

Although the sighting system 1 has been de-

scribed as an automatic radio sighting system, it is contemplated that an ordinary manually operated optical sighting device, such as a telescope, may be employed in conjunction with a conventional manually operated optical range finder in order to obtain the spherical coordinates (A_0, E_0 and D_0) of the present position of the target.

Referring again to Fig. 1, it may be considered that an ultimate function of the computing apparatus there disclosed is to produce angular displacements of shafts **8** and **9**, respectively proportional to the angle of train (A.T.) of the gun and the quadrant elevation (Q.E.) of the gun required for effective gun fire, and on shaft **10** an angular displacement proportional to the correct projectile time of flight (t_p). The operation of the computing apparatus in accomplishing the solution for angle of train will first be considered.

As shown, the present azimuth (A_0) shaft **2** is employed to actuate a permanent magnet generator **11**, which accordingly produces upon its output lead **12** a voltage signal corresponding in magnitude and polarity to the magnitude and sense of the rate of change or first time derivative ($\dot{A}_0$) of the present azimuth angle (A_0). This voltage signal is then introduced into the predicting circuit **13** where it is further successively differentiated in order to obtain the second and third derivatives ($\ddot{A}_0$) and ($\dddot{A}_0$) of the present azimuth angle. As will later be described in more detail, the predicting circuit **13** multiplies these successively higher derivatives by factors respectively proportional to corresponding powers of the time of flight which is received as a proportional rotation of input shaft **14** from shaft **10**, and the interconnecting shafts and gearing. The various products so obtained are then additively combined to produce on output lead **15** a voltage signal corresponding to the azimuth prediction correction (ΔA). This correction, which represents the change in the angular position of the target in azimuth during the projectile time of flight (t_p), is then introduced into the difference indicator **25**.

In order to obtain the azimuth ballistic correction (δ) which takes into account the variation of the projectile from a straight line course after it has left the gun, there is provided a ballistic mechanism **16**. The ballistic mechanism is adapted to receive, as proportional rotations of input shafts **17**, **18** and **19**, data corresponding to the angle of train (A.T.), quadrant elevation (Q.E.), and time of flight (t_p) from shafts **8**, **9** and **10**, respectively. Since the ballistic corrections will be influenced both by the presently existing atmospheric conditions and also by the muzzle velocity of the gun, there are provided knob and graduated scale arrangements **20**, **21**, **22** and **23**, by proper adjustment of which data corresponding to the change in muzzle velocity (ΔM.V.) from standard, the percentage change in air density ($\%\Delta\rho a$) from standard, and the velocity (V_W) and azimuthal direction (A_W) of the wind may be sent into the ballistic mechanism. The ballistic mechanism, having received these various input data, is then adapted to produce on its output lead **24** a voltage proportional to the azimuth ballistic correction (δ), as will later be described in more detail. This voltage signal is then also introduced into the difference indicator **25**.

The difference indicator **25** operates in conjunction with the angle of train servo **26** and

subtracting differential **27** to form a follow-up system, which system acts to angularly displace shaft **8** by an amount proportional to the present azimuth angle (A_0) appearing as a proportional displacement of shaft **2**, plus the azimuth prediction correction (ΔA) appearing as a proportional voltage on lead **15**, plus the azimuth ballistic correction (δ) appearing as a proportional voltage on lead **24**. Shaft **8** is thus positioned in accordance with angle of train (A.T.). Since the angle of train servo **26** drives shafts **8** and **29** equally, the angular displacement of shaft **29** also is proportional to angle of train (A.T.).

In operation the subtracting differential **27** produces on its output shaft **28** an angular displacement equal to the difference between the angular displacements of its two input shafts **29** and **2**, and therefore proportional to angle of train minus present azimuth angle (A.T.$-A_0$). The difference indicator **25** additively combines the azimuth prediction correction (ΔA) received on lead **15** and the azimuth ballistic correction (δ) received on lead **24**. It then makes a comparison between this sum ($\Delta A+\delta$) and the difference (A.T.$-A_0$) received on shaft **28**, and produces on its output lead **30** a voltage signal corresponding to the difference (dA) existing in these two quantities, if any.

Since this voltage signal (dA) appearing on lead **30** is employed to control the angle of train servo **26**, it will be apparent that the servo will drive shafts **8** and **29** until the voltage signal (dA) has been reduced to zero. When this condition is met, the following relationship holds:

$$(\Delta A+\delta)-(\text{A.T.}-A_0)=0$$

Re-arranging the above equation, we obtain the following equation:

$$\text{A.T.}=A_0+\Delta A+\delta$$

Accordingly, shafts **29** and **8** will have been angularly displaced by an amount corresponding to the present azimuth angle (A_0), plus the azimuth prediction correction (ΔA), plus the azimuth ballistic correction (δ), and therefore by an amount corresponding to the true angle of train (A.T.) required to hit the target.

Shaft **8** may then be employed to actuate an angle of train transmitter **31**, which may be of any suitable type, such as a conventional "Selsyn" or "Autogon," in order to transmit data corresponding to the correct angle of train (A.T.) to a remote gun battery by way of output lead **32**.

Similar apparatus is employed in order to compute the elevation prediction correction (ΔE) and the elevation ballistic correction (ϕ_s), and to produce upon shaft **9** an angular displacement proportional to the sum of present elevation angle (E_0) and these two corrections, that is, proportional to quadrant elevation (Q.E.). In general the apparatus employed for the solution in elevation has been given the same reference numeral as the corresponding azimuth apparatus, but has been primed. A quadrant elevation transmitter **31'**, which may be identical to transmitter **31**, is provided to convert the quadrant elevation signal appearing as proportional rotation of shaft **9** into corresponding electrical data appearing on lead **32'**. This quadrant elevation (Q.E.) may then also be transmitted electrically to a remote gun position.

An angular rotation of shaft **10** proportional to the projectile time of flight (t_p) is produced in an identical manner, although this is a little more difficult to understand since the corre-

sponding input data, appearing as an angular displacement of shaft 6, is in terms of slant range (D_0), a distance, whereas the output data required is in terms of time. However, it will be appreciated that the time of flight setting of shaft 10 may be treated as an equivalent slant range setting because the actual time of flight plus a ballistic correction is a quantity (t_pV) proportional to the slant range to the point of burst of a projectile. "V" is an arbitrary constant of proportionality which may be called the mean projectile velocity. The product (t_pV) is an arbitrary variable which may be called "equivalent range." Now, having everything in terms of distance, we can calculate a slant range prediction correction (ΔD) and a slant range ballistic correction (ρ), and we can employ a follow-up system to produce a rotation of shaft 29'' proportional to the present slant range (D_0) plus these corrections, and therefore proportional to the equivalent range setting (t_pV) required. In rotating shaft 29 by this amount, the time of flight servo 26'' angularly displaces shaft 10 by a proportional, but in this case not equal, amount. The proportionality factor is made equal to the mean projectile velocity (V) so that the angular displacement of shaft 10 corresponds to the true projectile time of flight (t_p).

This time of flight is then fed to the fuze converter and corrector 34, into which fuze dead time (F.D.T.) is also introduced as by knob and graduated dial 35. Fuze converter and corrector 34 is preferably of the type disclosed in copending application Serial No. 470,686 for "Gun Directing System," filed December 30, 1942 in the names of D. J. Campbell and W. G. Wing, although any other suitable type may be employed. As described in that application, time of flight (t_p) is first converted to a corresponding fuze setting by a suitable cam arrangement. A variable speed device is employed as a differentiating mechanism to obtain the rate of change in this fuze setting. This rate of change is then multiplied in the same variable speed by fuze dead time to obtain the total change in fuze setting which may be expected to occur in the dead time interval. This change in fuze setting is then added to the present fuze setting to obtain the corrected fuze setting which may be expected at the end of the dead time interval. Output shaft 36 from the fuze converter and corrector 34 is caused to have a rotation proportional to this corrected fuze setting (F). The corrected fuze setting (F) may then be transmitted to a remote point, as by transmitter 31'' and the electrical transmission channel 32''.

Before taking up the detailed description of predicting circuit 13, ballistic mechanism 16, and difference indicator 25, the various electronic and electro-mechanical calculating units employed as basic components throughout the system will first be described. These are shown in Figs. 6 through 8. The circuits of Figs. 6 to 8 are described and claimed in the application of Edward L. Ginzton, Serial No. 594,571, filed May 18, 1945.

Referring now to Fig. 6, there is shown a circuit useful in various ways for operating on voltage signals in the system. As shown, an electron tube 80, indicated as a triode, is provided having its grid connected to the ungrounded side of the direct voltage input signal (V_i). The cathode of tube 80 is connected to the grounded side of the input signal through resistors 81 and 82. The point 83 intermediate resistors 81 and 82 is connected through the variable resistor 84 to the negative side of the plate supply voltage, shown as battery 85. Battery 85 is grounded at a point intermediate its positive and negative terminals. The plate of tube 80 is connected to the positive side of the plate supply voltage through the resistor 86. A closed circuit is formed across the terminals of battery 85 through the resistors 86, 87 and 88, the last of which is variable. One output lead 89 is connected to a point 91 intermediate the resistors 87 and 88. The other output lead 90 is connected to the point 83. A grounded output lead 92 may also be used, if desired.

The electron circuit through the tube may be considered as traveling from ground through resistors 82 and 81, through tube 80 and resistor 86 to the positive side of battery 85, and then back to ground. Another closed circuit is formed from ground through resistor 82 and variable resistor 84 to the negative side of battery 85 and then to ground.

With zero voltage signal (V_i) applied to the grid of tube 80, that is, with the quiescent value of current flowing through the tube, variable resistor 88 is adjusted until the point 91 and output conductor 89 are at ground potential. At the same time, variable resistor 84 is adjusted until the point 83 and output conductor 90 are at ground potential.

If a positive voltage signal (V_i) should be received, it will be apparent that because of the increase of current flow through resistor 86 the potential of point 93 will decrease. Accordingly, the potential of point 91 and that of output conductor 89 will decrease to a negative potential proportional to the input voltage signal (V_i). At the same time, due to the increase of current flow through resistor 82, the potential of point 83 and that of the output conductor 90 will increase in the positive direction by a corresponding amount. Similarly, should a negative voltage signal be received, a proportional positive signal will be produced on output lead 89 and a proportional negative signal will be produced on lead 90.

Moreover, due to an increase of current flow through resistors 82 and 81 resulting from a positive input signal impressed upon the grid, the cathode of tube 80 will become more positive causing the grid to become more negative with respect to the cathode. This will tend to decrease current flow through the tube thus opposing the effect of the received signal. In this way, inverse feedback is provided which stabilizes the ratio of output to input voltage signals by eliminating the effects of changes in the tube characteristics caused by age of the tube, variations in external conditions, such as temperature and humidity, and other reasons.

The circuit shown in Fig. 6 may therefore be used for two different purposes. It may be used as a "follower" circuit in which an output voltage signal is provided across output conductors 90 and 92, which is of the same polarity and proportional to the input signal (V_i). Such a follower circuit is employed in a potentiometer multiplying unit, which will later be described, in order to produce an output voltage signal from which current may be drawn, said output voltage signal being proportional to an input voltage signal from which it is undesirable to draw current. The circuit shown in Fig. 6 may be also employed as a "reversing" circuit wherein an output voltage signal may be obtained across output conductors 89 and 92 proportional in magnitude to the input signal but of opposite polarity.

Referring now to Fig. 7, there is shown a potentiometer unit useful for multiplying, obtaining functions of an independent variable, and for a combination of these two purposes. As there shown, one terminal 96 of the potentiometer 95 is connected to the ungrounded side of the input voltage signal (V_1). The other terminal 97 is grounded. The contact arm 98 of the potentiometer 95 is rotated in accordance with the shaft displacement signal (x) from the input shaft 99. The potentiometer 95 is wound so that the resistance from the grounded terminal 97 to a particular point on the potentiometer is proportional to the value of the function F (x) corresponding to the value of x represented by that point. Conductor 100, which is electrically connected to contact arm 98, is introduced into a follower circuit 101 which may be of the type shown in Fig. 6. The output voltage of follower circuit 101 which appears on output lead 102 is then proportional to the desired output signal.

It will be apparent that the voltage between conductor 100, which is connected to the contact arm 98, and ground will be proportional to the voltage input signal (V_1) and also proportional to the function F (x) represented by the position of contact arm 98. The voltage of conductor 100 is therefore proportional to $F(x) \cdot (V_1)$. This is only true, however, when the voltage across conductor 100 is on open circuit, that is, when it is drawing no current. In order to be able to use this signal without drawing current therefrom, the follower circuit 101 is provided, and the output voltage appearing on conductor 102 may be employed as the useful signal from which current supplied by the plate supply voltage of follow circuit 101, may be drawn without causing any inaccuracy. As shown and described, the potentiometer unit of Fig. 7 constitutes a "function and multiplying" unit wherein a voltage signal is obtained on output lead 102 proportional to the product of the input signal (V_1) and a predetermined function of the input shaft displacement signal (x).

It will be apparent that by linearly winding potentiometer 95, a voltage output signal ($x \cdot V_1$) may be obtained, which is proportional to the product of the voltage input signal (V_1) and the shaft displacement signal (x). When the potentiometer unit is used in this way, it will be referred to simply as a "multiplying" unit. A simplified modification may also be used simply as a "function" unit, in which case, the potentiometer 95 would be energized from a constant source of direct voltage and would be wound in accordance with the desired function. In such case, an output voltage signal would be produced proportional to the desired function of the shaft displacement input signal. With potentiometer 95 constantly energized and linearly wound, a "conversion" unit is obtained which may be employed simply to convert a shaft displacement input signal to a proportional voltage output signal. In the drawings of Figs. 2, 4 and 5, the potentiometer unit of Fig. 7 is schematically shown, and the particular one of its four possible functions is indicated by appropriate initials marked within the unit.

Referring now to Fig. 8, wherein there is shown a circuit for obtaining the algebraic sum of two voltage input signals (V_1 and V_2), there are provided two electron tubes 104 and 105 which are indicated as tetrodes, although pentodes would be equally suitable. The ungrounded side of one voltage input signal is applied to the control grid of tube 104 while the ungrounded side of the other voltage input signal is applied to the control grid of tube 105. A plate supply battery 106, grounded at an intermediate point between its positive and negative terminals, supplies positive plate potential to the plates of each of the tubes through the resistor 107. The negative terminal of battery 106 is also connected to the plates of the tubes through the variable resistor 108 and resistor 109. The voltage appearing at the point 110 between resistors 108 and 109 is fed through a reversing circuit 111, which may be of the type shown in Fig. 6, and which supplies on its output lead 112 a voltage signal proportional to the sum of the two input signals (V_1+V_2).

The cathode of tube 104 is connected to ground through the biasing resistor 113 and inverse feed back resistor 114, and the cathode of tube 105 is connected to ground through respectively identical biasing and inverse feed back resistors 115 and 116. The negative terminal of the battery is connected to a point 117 midway between resistors 113 and 114 through the variable resistor 118. A similar connection is made from the negative terminal of the battery through the variable resistor 119 to a point 120 midway between resistors 115 and 116. The screen grids of both tubes may be connected to the positive terminal of the battery, as shown. With both tubes 104 and 105 operating at their quiescent conditions, that is, with both input signals at zero potential, the variable resistors 108, 118 and 119 are adjusted so that the points 110, 117 and 120, respectively, are at zero potential.

In operation, when a positive voltage input signal (V_1) is received on the control grid of tube 104, the resulting increase in current flow through resistor 107 lowers the potential applied to the plates of both tubes. Since both tubes are tetrodes, this reduced plate voltage will have substantially no effect on the flow of current through tube 105. The reduction of the plate potential, however, will cause the potential of point 110 to become negative by an amount corresponding to the positive input voltage signal (V_1). Should a negative voltage input signal be received on the control grid of tube 104, the potential of point 110 will become positive by a corresponding amount. In a similar way, the receipt of a positive or negative voltage input signal on the control grid of tube 105 will cause the potential of point 110 to become more negative or more positive, respectively, by a corresponding amount. Since the amount of current flowing through resistor 107 is the sum of the currents flowing through each of the tubes, and since the current through each of the tubes is dependent only on the input voltage signal applied to its control grid and is independent of the current flow through the other tube, it will be apparent that the potential at point 110 will be proportional in magnitude to the algebraic sum (V_1+V_2) of the received input signals, but opposite in polarity. The polarity of this resultant potential is reversed in reversing circuit 111 so that the voltage signal appearing on output lead 112 corresponds both in polarity and magnitude to the algebraic sum (V_1+V_2) of the received input signals.

Inverse feed back for tube 104 is provided by resistors 113 and 114 and for tube 105 by resistors 115 and 116. As the current through tube 104 increases or decreases as the resultant of the receipt of a voltage signal upon its control grid, the resulting change in cathode potential caused

by the change in current flow through resistors 113 and 114 will tend to oppose the effect of the received signal voltage applied to the grid. An increase or decrease in current flow through resistors 115 and 116 acts in a similar way in opposition to the received voltage signal (V_2) causing the increase or decrease. There is thus provided the required inverse feed back required for effecting an accurate summation of the received signals.

It will be appreciated that the sum circuit characterized by Fig. 8 is not limited to obtaining the algebraic sum of only two voltage input signals, but that any number of voltage input signals could be algebraically added. For each additional input signal another tetrode would be required connected in the circuit identically with tubes 104 and 105 so that its plate current also would flow through the common plate resistor 107.

Returning now to a consideration of the prediction problem, that is, the manner in which the predicting circuit 13 solves for the prediction corrections (ΔA, ΔE and ΔD) in azimuth, elevation, and slant range, respectively. It may be said that no matter in what manner the target may be moving, each of its coordinates will instantaeously have some specific law of motion which defines the value of that coordinate as a function of time, and which may be expressed for the azimuth coordinate, for instance, by the following formula:

$$A(t)=A_0+a_1t+a_2t^2+a_3t^3+\cdots+a_nt^n$$

wherein zero time is taken as the time at which we are attempting to perform the predicting, that is, when $A=A_0$, and the a's are unknown coefficients. If then it is desired to determine the angular orientation of the target in azimuth at a time (t_p) later, we may employ a Taylor series as follows:

$$A(t_p)=A_0+\dot{A}_0(t_p)+\frac{\ddot{A}_0(t_p)^2}{2}+\frac{\dddot{A}_0(t_p)^3}{6}+\cdots+\frac{^{n\text{ dot}}A(t_p)^n}{n!}$$

The azimuth prediction correction (ΔA) is then equal to the sum of all the terms in the above expression subsequent to the first, or A_0 term.

$$\Delta A=\dot{A}_0(t_p)+\frac{\ddot{A}_0(t_p)^2}{2}+\frac{\dddot{A}_0(t_p)^3}{6}+\cdots+\frac{^{n\text{ dot}}A(t_p)^n}{n!}$$

This expression is employed in predicting circuit 13 to obtain a voltage signal proportional to the azimuth prediction correction (ΔA).

As shown in Fig. 2, the voltage from permanent magnet generator 11 appearing on input lead 12 and corresponding to the first derivative ($\dot{A}_0$) of the azimuth angle (A_0), is introduced into a sum circuit 41, which may be of the type disclosed in Fig. 8, as on lead 39, and also into a smoothing and differentiating circuit 42, as on lead 40. As will more fully be explained hereinafter, smoothing and differentiating circuit 42 is adapted to further successively differentiate the input first derivative data, thereby producing on output leads 43 and 44 voltage signals corresponding to the second ($\ddot{A}_0$) and third ($\dddot{A}_0$) derivatives of the azimuth angle.

Three potentiometer multiplying units 45, 46 and 47, are provided, the contact arm of each of which is actuated in accordance with a required value of time of flight (t_p) received as a proportional rotation of input shaft 14. Potentiometer unit 47 is energized in accordance with the third derivative ($\dddot{A}_0$) and its contact arm is rotated proportionally to one-third time of flight (t_p), by reduction gearing 47', to produce upon its output lead 48 a voltage proportional to $\frac{1}{3}\dddot{A}_0t_p$. This voltage is then added in the sum circuit 49 to the voltage appearing on lead 43 to produce upon lead 50 a voltage proportional to $\ddot{A}_0+\frac{1}{3}\dddot{A}_0t_p$.

The voltage signal thus appearing on lead 50 is then multiplied in potentiometer unit 46 by one-half the time of flight, to produce upon lead 51 a voltage proportional to $\frac{1}{2}\ddot{A}_0t_p+\frac{1}{6}\dddot{A}_0(t_p)^2$. This voltage is then added to the voltage received on input lead 12, and the sum is again multiplied by the time of flight in potentiometer multiplying unit 45 to produce a voltage on output lead 15 proportional to $\dot{A}_0t_p+\frac{1}{2}\ddot{A}_0t_p^2+\frac{1}{6}\dddot{A}_0t_p^3$. This voltage may then be taken as proportional to the azimuth prediction correction (ΔA) as derived from Taylor's series since mathematical investigation of the anti-aircraft problem discloses that for the types of target courses most likely to be encountered under combat conditions the first three terms of this series provide sufficient data to obtain the degree of accuracy required in the final solution.

In Fig. 3 there is shown apparatus which may be employed in smoothing and differentiating circuit 42 to accomplish the function of that circuit. As there shown, the voltage received on input lead 40 corresponding to the first derivative ($\dot{A}_0$) of present azimuth angle (A_0) is placed across a series circuit consisting of the condenser 56 and resistor 57. Since the charging current flowing into condenser 56 will be proportional to the time rate of change of the voltage appearing on lead 40, the current through resistor 57, consisting only of this changing current, will be proportional to the time rate of change of the first derivative ($\dot{A}_0$) or, in other words, proportional to the second derivative ($\ddot{A}_0$).

The voltage across resistor 57, corresponding therefore to the second derivative ($\ddot{A}_0$) of the present azimuth angle, is fed to the grid of an electron tube 58. The cathode of tube 58 is connected to ground through the resistor 59 and the parallel circuit consisting of the condenser 60 and resistor 61. The plate supply battery 62 has a point intermediate to its positive and negative terminals grounded. The plate of tube 58 is connected directly to the positive side of battery 62. The negative side of battery 62 is connected through the variable resistor 63 to a point intermediate resistors 59 and 61. It will be evident that electron tube 58 and its associated circuit elements constitute a "follower" circuit of the type shown in Fig. 6, except for the addition of the condenser 60 across resistor 61.

As is well known, the present azimuth data received from the radio sighting system 1 and appearing as a proportional rotation of shaft 2, will always have some erratic perturbations superimposed upon the true value represented thereby. This is caused by the impossibility of obtaining perfect servo systems in the radio sighting system 1 for accurately following the target, by backlash in the gearing, and so forth. These erratic variations appearing on shaft 2 will be reflected as corresponding variations in the first derivative voltage signal appearing on leads 12 and 40. These variations in the first derivative data in turn will be reflected into the voltage signal appearing across resistor 57 and represent-

ing the second derivative ($\ddot{A}_0$) of the azimuth angle. The purpose of condenser **60** is to operate in conjunction with resistor **61** to form a simple smoothing circuit in order to average out the resulting false variations in the second derivative data. Accordingly, there is produced an output lead **43** a voltage signal $(\ddot{A}_0)_s$ proportional to a smoothed measure of the second derivative voltage signal appearing across resistor **57**.

In order to obtain a voltage on lead **44** proportional to the third derivative ($\dddot{A}_0$) of the present azimuth angle, the voltage appearing on lead **43**, representing the second derivative ($\ddot{A}_0$), may be re-differentiated and re-smoothed by introducing it into apparatus identical with that just described for obtaining the second derivative. If desired, more refined circuits for differentiating and smoothing may be employed. Also, in obtaining the azimuth prediction correction (ΔA), only the first three derivatives have been utilized. It will be apparent that by applying the principles of operation of the invention which have been described, it is possible to carry as many terms of the Taylor series as is desired.

Since the elevation prediction correction (ΔE) and the slant range prediction correction (ΔD) may be obtained in the same manner as described for obtaining the azimuth prediction correction (ΔA), a further description of the predicting apparatus is not necessary.

In Fig. 4 there is shown the ballistic mechanism **16** of Fig. 1, the purpose of which is to receive time of flight (t_p), quadrant elevation (Q. E.) and angle of train (A. T.), represented by the displacements of shafts **10**, **9** and **8**, respectively, and to produce from these input signals and from other input signals corresponding to the change in muzzle velocity (Δ M. V.), percentage change in air velocity ($\%\Delta\rho a$), and the velocity and azimuthal direction of the wind (V_w and A_w), the azimuth, elevation and slant range ballistic corrections (δ, ϕ_s and ρ) as proportional voltages or output leads **24**, **24'** and **24''**, respectively.

Angle of train (A. T.) received on input shaft **17** is introduced into a wind resolver **122**. The purpose of the wind resolver, which also receives the velocity and azimuthal direction of the wind from knobs **22** and **23**, respectively, is to produce on its output shafts **123** and **124** angular displacements respectively proportional to the rear-wind velocity (W_r) and the cross-wind velocity (W_c). The wind resolver may consist of a differential in which the difference between the azimuthal wind direction (A_w) and the angle of train (A. T.) is obtained. This difference may be introduced into a disc and slide mechanism of the type which is employed in U. S. Patent No. 2,065,303, entitled "Apparatus for the Control of Gun Fire" and issued December 22, 1936 in the names of E. W. Chafee et al. for the purpose of resolving the coordinates (R_0) and (A_0) of the present position of the target in the horizontal plane into the corresponding rectilinear coordinates (x_0) and (y_0). The disc and slide mechanism is employed in a similar manner in the present device to compute the required components of wind velocity (W_r and W_c) along and across the line of fire, from the velocity of the wind and its angular direction with respect to the line of fire. Such a wind resolver, as has herein been described, is shown and described more completely in the aforementioned copending application Serial No. 470,686, wherein it is used for an identical purpose.

The conversion units **126** and **125**, respectively, actuated from shafts **124** and **123**, produce on their output leads **128** and **127**, voltage signals proportional to the cross-wind velocity (W_c) and the rear-wind velocity (W_r), respectively. The conversion unit **129**, actuated in accordance with the percentage change in air density ($\%\Delta\rho a$) from shaft **130** and knob **21**, produces a proportional voltage on its output lead **131**. Similarly, the conversion unit **132**, which is actuated in accordance with the change in muzzle velocity (Δ M. V.) from knob **20** and shaft **133**, produces on its output lead **134** a voltage proportional to change in muzzle velocity.

The desired azimuth ballistic correction (δ) is calculated in the ballistic mechanism in accordance with the formula:

$$\delta = f_1(t_p)\, g_1 \text{ (Q. E.)} + W_c f_2(t_p)\, g_2 \text{ (Q. E.)}$$

In this formula and the following formulae, subscripts f and g are used to indicate different functions of time of flight and quadrant elevation, respectively. These functions are obtained from data given in firing tables which have been empirically compiled.

In order to compute the azimuth ballistic correction (δ) in accordance with the above formula, the function unit **135** and the function and multiplying unit **136** are actuated in accordance with time of flight (t_p) from input shaft **19**, and the function and multiplying units **137** and **138** are actuated in accordance with quadrant elevation (Q. E.) from input shaft **18**. The predetermined function of time of flight $f_1(t_p)$ produced by the function unit **135** is multiplied by the proper predetermined function of quadrant elevation g_1 (Q. E.) in the function and multiplying unit **137** so that there is produced on lead **139** a voltage proportional to the first quantity of the equation for the azimuth ballistic correction (δ).

In a similar manner, the cross-wind velocity (W_c) is successively multiplied by the proper function $f_2(t_p)$ of time of flight and the proper function g_2 (Q. E.) of quadrant elevation in the function and multiplying units **136** and **138**, respectively. This product, which is equal to the second quantity in the equation for the azimuth ballistic correction (δ), is produced as a proportional voltage signal on lead **140**. The sum circuit **141** operates to add the input voltages received on leads **139** and **140** and to produce on its output lead **24** a voltage proportional to the azimuth ballistic correction (δ) in accordance with the above formula.

The elevation ballistic correction or superelevation (ϕ_s) is computed in accordance with the following formula:

$$\phi_s = f_3(t_p)\, g_3 \text{ (Q. E.)} + W_r f_4(t_p)\, g_4 \text{ (Q. E.)} + \%\Delta\rho a f_5(t_p)\, g_5 \text{ (Q. E.)} + \Delta \text{ M. V. } f_6(t_p)\, g_6 \text{ (Q. E.)}$$

wherein the first quantity is the elevation ballistic correction existing under standard conditions and the next succeeding quantities take into consideration the actual conditions of rear-wind, air density, and muzzle velocity existing at the time of the solution.

In order to solve for the elevation ballistic correction (ϕ_s) according to the above formula, the function unit **142** and the function and multiplying units **143**, **144** and **145** are all actuated in accordance with the time of flight (t_p) from shaft **19**, and the function and multiplying units **146**, **147**, **148** and **149** are actuated in accordance with quadrant elevation (Q. E.) from shaft **18**. The function and multiplying units **143**, **144** and **145**

are respectively energized in accordance with the rear wind velocity (W_R) percentage change in air density ($\%\Delta\rho_a$), and the change in muzzle velocity (ΔM. V.) from leads 127, 131 and 134, respectively.

In accordance with the theory of operation of the function and multiplying units, which by now should be well understood, there are produced as proportional voltages on leads 150, 151, 152 and 153, measures of each of the four quantities comprising the elevation ballistic correction (ϕ_s). The sum circuit 154 operates to combine these four quantities and to produce on lead 24' voltage proportional to the elevation ballistic correction (ϕ_s) in accordance with the above set out formula.

The slant range ballistic correction (ρ) is similarly computed in accordance with the following formula:

$$\rho = f_7(t_p) + f_8(t_p)\, g_7(\text{Q.E.}) + W_R f_9(t_p)\, g_8(\text{Q.E.}) + \%\Delta\rho_a f_{10}(t_p)\, g_9(\text{Q.E.}) + \text{M.V.} f_{11}(t_p)\, g_{10}(\text{Q.E.})$$

wherein the first two quantities are sufficient to compute the slant range ballistic correction under normal conditions and the last three take care of existing variations from the normal conditions.

As shown, the function units 155 and 156, and the function and multiplying units 157, 158 and 159, are actuated from the time of flight shaft 19, and the function and multiplying units 160, 161, 162 and 163 are actuated in accordance with quadrant elevation from shaft 18. The function and multiplying units 157, 158 and 159 are respectively energized from leads 127, 131 and 134 in accordance with the rear wind velocity and the variations in air density and muzzle velocity from standard conditions, respectively. The various function and function and multiplying units operate to produce on leads 164, 165, 166, 167 and 168 voltages proportional to the various quantities comprising the slant range ballistic correction (ρ). The sum circuit 169 performs the required algebraic addition of these various quantities in accordance with the above formula. There is accordingly produced on output lead 24'' a voltage proportional to the slant range ballistic correction (ρ).

Referring now to Fig. 5 wherein the azimuth component of the difference indicator 25 of Fig. 1 is schematically shown, a conversion potentiometer unit 64 is provided to convert the angular displacement of input shaft 28 into a voltage on output lead 65 corresponding in magnitude but having an opposite polarity. It will be recalled that the angular displacement of shaft 28 is proportional to the difference between the angle of train (A. T.), appearing as a proportional rotation of shaft 29, and the present azimuth angle (A_0), appearing as proportional rotation of shaft 2. The voltage signal appearing on lead 65, therefore, corresponds to the quantity $-(\text{A.T.}-A_0)$. This voltage is introduced into a sum circuit 66. Also introduced into sum circuit 66, as on leads 15 and 24, respectively, are voltage signals corresponding to the azimuth prediction correction (ΔA) and the azimuth ballistic correction (δ). The sum of all these input voltage signals is thus produced on output lead 30. Accordingly, the voltage appearing on output lead 30 is the required signal voltage (dA) for actuating the angle of train servo 26 as expressed by the following relationship:

$$dA = (\Delta A + \delta) - (\text{A.T.} - A_0)$$

As previously stated, shafts 8 and 29 will continue to be driven by servo 26 until voltage signal

(dA) has been reduced to zero, at which time shaft 8 will have been angularly displaced an amount proportional to the angle of train (A.T.) at which the gun must be positioned for effective gun fire. The elevation and slant range components of difference indicator 25 obtain the elevation and slant range voltage signals (dE and dD) in an identical manner.

It will be apparent that electrical calculating devices for performing the various operations accomplished by the devices shown in Figs. 6 through 8 could be designed to operate on alternating current voltage signals as well as direct current voltage signals. If desired, such devices could then be incorporated in the gun directing system described, with only slight modification of the system, thus providing a gun directing system operating on alternating current throughout. It is, therefore, not intended that the present invention be limited to the use of direct current voltage signals.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. A predictor comprising, in combination, an input terminal adapted to receive a quantity proportional to the first derivative of a variable, a smoothing and differentiating circuit for converting the quantity applied to the input terminal into second and third derivatives respectively, a plurality of potentiometers each having a slidable tap and a common driving means adapted to be rotated in proportion to an independent variable, connections for applying the third derivative quantity to the first potentiometer, a summing circuit with input connections from a second derivative terminal of the smoothing and differentiating circuit and from the tap of the first potentiometer, an output connection from said summing circuit to the second potentiometer, a second summing circuit with input connections from the tap of the second potentiometer and from the input terminal of the apparatus, and an output connection to the third potentiometer, the tap of the third potentiometer having an output terminal at which the predicted value appears.

2. A prediction circuit for a gunfire director comprising, in combination, an input terminal to which a voltage may be applied proportional to the first derivative of one of the independent variables of a prediction problem representing one of the coordinates of the target, a differentiating circuit having an input from said terminal, a first output terminal at which a second derivative voltage appears, and a second output terminal at which a third derivative voltage appears, three potentiometers with a driving shaft adapted to move in proportion to time of flight of a projectile, each of said potentiometers comprising a pair of relatively movable elements, one of which comprises an impedance winding and the other of which comprises a sliding tap, first and second summing circuits, an input connection from the third derivative terminal to the winding of the first potentiometer, input connections to the first summing circuit from the second derivative terminal and the tap of the first potentiometer, an output connection from

the first summing circuit to the winding of the second potentiometer, input connections from the apparatus input terminal and the tap of the second potentiometer to the second summing circuit, an output from the second summing circuit to the winding of the third potentiometer, and an output connection from the tap of the third potentiometer on which a voltage representing predicted value appears.

3. A predicting circuit for a gunfire director comprising, in combination, an input terminal to which a function of one of the coordinates of the moving target may be applied, a differentiating circuit having an input connection from said terminal, and a plurality of output terminals at which appear quantities representing successively higher derivatives of the quantity applied to the input terminal, a plurality of summing circuits equal to the number of output terminals of the differentiating circuit, a plurality of potentiometers, one greater than the number of summing circuits, each of the potentiometers except the last having one of said summing circuits associated therewith, each of said summing circuits having one input from one of the said terminals and a second input from one of the potentiometers and having an output to a succeeding potentiometer, the first potentiometer having an input from the highest derivative terminal of the differentiating circuit, whereby the last potentiometer has an output representing the Taylor series in which the number of terms is equal to the number of potentiometers employed, and terms of the Taylor series are power functions of projectile time of flight and derivative functions of the coordinate of the target.

4. Apparatus for computing a Taylor series in terms of a first and second variable, comprising means for differentiating a first variable, a terminal at which a quantity proportional to the first derivative appears, means for successively differentiating, having terminals at which successively higher derivatives appear, a plurality of potentiometers equal in number to the number of derivative terminals, each potentiometer comprising a pair of relatively movable elements, one of which consists of a winding and the other of which consists of a slidable tap, means for producing relative motion of said potentiometer elements in proportion to the second of two variables in terms of which the Taylor series is to be produced, and a plurality of summing circuits one less in number than the number of potentiometers, the first of said potentiometers having an input to its winding from the highest derivative terminal, all of the potentiometers except the last having a summing circuit associated therewith, each of said summing circuits having a pair of inputs, one from the tap of the potentiometer with which it is associated, and a second from the derivative terminal, one lower in order than the derivative terminal to which the summing circuit of the preceding potentiometer is connected, and each summing circuit having an output terminal connected to the winding of the next succeeding potentiometer, whereby a quantity proportional to the sum of the Taylor series terms appears upon the tap of the last potentiometer.

5. An electrical predicting circuit comprising, in combination, a differentiating device having an input terminal to which a derivative quantity is adapted to be applied, output terminals to which successively higher derivatives of an input quantity are supplied by the differentiating circuit, a plurality of potentiometers having relatively movable members comprising windings and taps respectively, and a common driving means therefor movable in proportion to the second quantity, a plurality of summing circuits one less in number than the number of potentiometers, each summing circuit having an output connection to one of the potentiometers, and a pair of input connections, one from one of the potentiometer taps and the other from one of the said derivative terminals, whereby a quantity proportional to the predicted value appears upon the tap of the remaining potentiometer.

6. Apparatus for computing a series of terms representing a function of first and second variables, said apparatus comprising an input terminal, means for differentiating an input quantity to produce successively higher derivatives of the first variable with terminals at which such derivative quantities appear, a plurality of potentiometers and summing circuit means, each of said potentiometers comprising a pair of relatively movable elements, one of which is a winding and the other of which is a sliding tap and having a common driving connection for producing relative movement of the elements of the potentiometers proportionally to the second variable, said summing circuit means having dual input connections from successively higher derivative terminals and successive potentiometer taps respectively, and the last of said potentiometer taps having an output circuit at which the computed value appears.

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