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HUMAN SUPERVISION AND MICROPROCESSOR  
CONTROL OF AN OPTICAL TRACKING SYSTEM

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SUMMARY

Gunners using small calibre anti-aircraft systems have not been able to track high-speed air targets effectively. Substantial improvement in the accuracy of surface fire against attacking aircraft has been realized through the design of a director-type weapon control system. This system concept frees the gunner to exercise a supervisory/monitoring role while the computer takes over continuous target tracking. This change capitalizes on a key consideration of human factors engineering while increasing system accuracy. The advanced system design, which uses distributed microprocessor control, is discussed at the block diagram level and is contrasted with the previous implementation.

INTRODUCTION

The allocation of system functions between man and machine is one of the key elements of human factors engineering. Typically, this allocation is determined by various technical specialists working closely together as an interdisciplinary team. One of the problems faced by system designers is that technical, cost, and operational constraints acting alone or in combination may override human factors considerations thereby jeopardizing the effectiveness of a system. This situation has plagued the designers of closed-loop target tracking systems which, for one reason or another, must use the human operator as a key element in the tracking loop.

Very early gunfire control systems gave the human operator no tracking assistance whatever. The operator was required to estimate all lead and superelevation angles and, in smaller systems, move the weapon as well. With the advent of power-driven mounts, the operator was no longer required to move the sighting mechanism, but, the difficult task of predicting future target position remained. Although systems designed to estimate future target position automatically contained inherent instabilities, performance improved over earlier systems. On an absolute basis, however, the accuracy of the gunfire delivered against fast-moving targets was still relatively poor. Increasing refinements in control system technology incorporating the use of human operators continued to yield improvements (see references 1 through 6), but manned systems were still less accurate than unmanned ones.

As an alternative to providing the human controller with various forms of assistance, for non-maneuvering targets, the principle of decoupling the gunner from the loop was advanced by Lockheed Electronics Company (LEC), where planning sessions dealt with the development of an improved small calibre weapon control system using optical tracking techniques. But a completely automated system did not meet program requirements, so another alternative was suggested: "Since we must have an operator in the tracking system, can he be removed immediately after target acquisition and retained as a performance monitor to supply minor corrections if the occasion demands them?" If applied successfully, such a solution would enable the system designers to free the operator from repetitive tasks while improving the performance of the system. The operator would initiate the track and then be removed quickly from the primary loop when the automated system could maintain the track. The operator could retain an overview sufficient to permit the simpler task of inserting corrections when needed. If the concept could be applied successfully, the goal of many man-machine system designers would be achieved: The operator would supervise system activity and not be burdened with the constant and demanding task of processing system information. Through such reallocation of system functions between man and machine, a low-cost, highly accurate manned fire control system could be designed. The usual role of the operator as an integral element in the control loop would be changed by deemphasizing track loop dependence on the non-linear human transfer function.

After a number of design studies, computer simulations, and laboratory implementations, a design emerged that worked so well in practice that U.S. Patent No. 4,004,729 (reference 7) was awarded. The system performs as well as a fully automatic system and has been implemented in an existing U.S. Army anti-aircraft weapon. A shipboard version is currently in production.

#### SYMBOLS

$E_e$	Voltage, tracking error
$E_g$	Voltage, gun rate loop command
$E_R$	Voltage, rate gyro
$E_s$	Voltage, sight rate gyro loop command
$V_s$	Voltage, sight rate aid
$V_g$	Voltage, gun rate aid
$\theta_g$	Gun line position angle, with respect to space
$\theta_s$	Sight line position angle, with respect to space
$\theta_{s/g}$	Sight line position angle with respect to gun line ( $\theta_s - \theta_g$ )

$\theta_A$	Radar line position angle with respect to space
$\theta_T$	Target position angle with respect to space
$\epsilon$	Target tracking position error with respect to space: ( $\theta_T - \theta_S$ ) in optical track; ( $\theta_T - \theta_A$ ) in radar track
CX	Synchro transmitter
$\lambda$	Lead angle
$G_1$	Dynamics of director (Laplace Transform)
$G_2$	Dynamics of plant (Laplace Transform)
$K_1$	} Magnitude of gain
$K_2$	
$K_3$	
S	Laplace Transform ( $j\omega$ )

#### MANNED WEAPON CONTROL TECHNOLOGY

Figure 1 is a stylized description of the essential elements of both prior state of the art gunnery and the principles set forth in Patent No. 4,004,729.

System operational concepts are reviewed to permit distinctions to be made between the new system design and earlier designs.

#### BASIC SYSTEM CONFIGURATION

Many small calibre (20mm to 40mm) gun mounts are manned in order to avoid the higher cost of a remote, full-track gun fire control system (GFCS). By using the operator to perform the target position sensing function in acquiring and tracking the target, an angle tracking radar or electro-optical system is not required, thus significantly reducing system cost. In this case, target range data only is supplied by the radar system or by a laser system.

The present state-of-the-art GFCS configuration consists of five major subsystems:

1. Gun/Turret servos, elevation and azimuth.
2. Optical gunsight servos, elevation and azimuth.

3. Radar Antenna Pedestal servos, elevation and azimuth.
4. Microcomputer, digital.
5. Operator/Stick.

Although the subsystems and their axes can be combined in many geometrical arrangements, a configuration most commonly found is shown in figure 1. The optical gunsight, radar antenna, microcomputer, and operator/stick subsystems are all mounted on the turret azimuth platform along with the gun elevation drive mechanism.

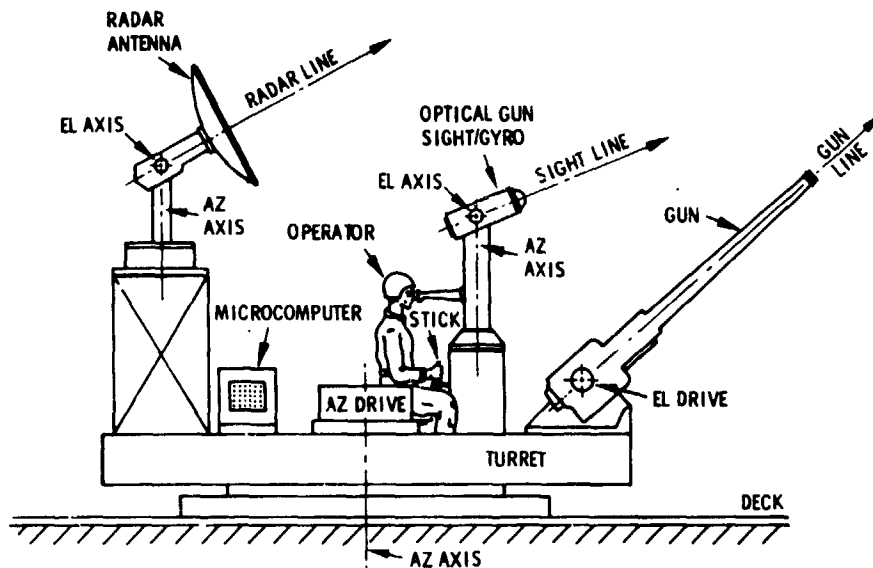


Figure 1. Manned Weapon Control System - Basic Configuration

In the configuration selected for discussion, notice that all three elevation axes are mounted parallel to the turret deck. So, for example, if the gun and radar elevation position servos are slaved to the optical sight position (with respect to the turret deck), the gun line and the radar line would follow and be parallel to the sight line in space (ignoring gun lead angles for the moment). Notice further that both the radar and sight azimuth axes are mounted on top of and parallel to the turret azimuth axis. Therefore, the radar and sight lines in azimuth are not required to be parallel to the gun line in azimuth. (The gun line is actually the turret azimuth position.) So, there is a relative motion problem to contend with in azimuth. Both the sight and the radar azimuth servos are positioned relative to the gun azimuth servo. For large angles of travel, the turret azimuth drive transports both the sight and the radar azimuth servos. In other words, the sight azimuth servo and the radar azimuth servo go along on the turret for a "free ride". It is important to visualize the relative motion relationships among all six axes before trying to understand how the gun fire control system physically functions.

There are many ways in which the five subsystems can be combined and controlled to form a weapon control system. In final analysis, however, the GFCS usually uses the computer and operator/stick subsystems to coordinate and provide hierarchial feedback control of the gun, sight, and radar subsystems in three major modes of operation: (1) target acquisition, (2) target tracking, and (3) ballistics solution and generation of gun lead angles. The scope of this paper is confined to examining man-machine interface configurations in the target tracking mode of operation.

Before presenting a description of the new director-type Sharpshooter system, a brief explanation of the earlier disturbed-line-of-sight system will demonstrate how the director-type control significantly improves the relationship between the human visual/motor system and the machine system.

PRIOR-ART: THE DISTURBED-LINE-OF-SIGHT SYSTEM

Most man-in-the-loop weapon control systems developed in the past can be characterized as Disturbed-Line-of-Sight systems (DLLOS). In a DLLOS system, the human operator plays a key role by becoming a cascaded component in the target tracking feedback loop as shown in figure 2.

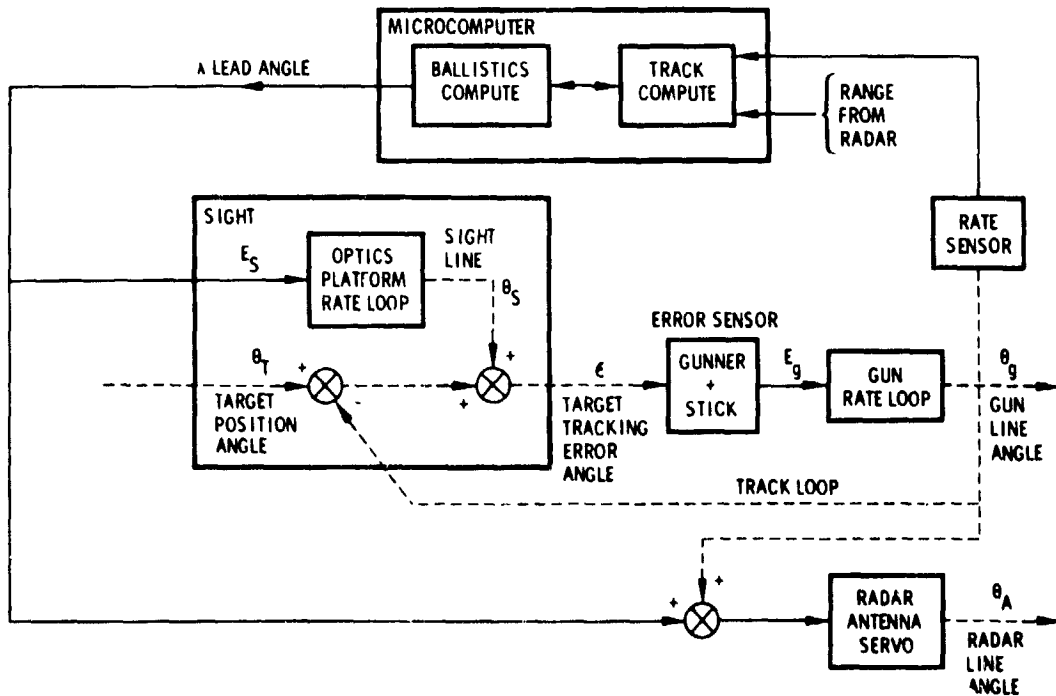


Figure 2. Disturbed Line-of-Sight Track Loop - Conceptual Model

In order to explain how the DLOS system works, consider the case where an airplane (target) is flying at a constant altitude in a circle, at the center of which is the gun mount. Elevation angles of sight, radar, and gun lines are equal and constant. With lead angle  $\lambda$  in figure 2 equal to zero, the gunner looks through the sight and observes the azimuth tracking error  $\epsilon = (\theta_T - \theta_g)$  by comparing the position of the target with the center of the gunsight reticle. By controlling the stick voltage output  $E_g$ , the gunner commands the speed of the gun in azimuth to make the speed of the gun line  $\dot{\theta}_g$  and the sight line  $\dot{\theta}_s$  equal to the speed of the target  $\dot{\theta}_T$  when the center of the reticle is as close to the target as the human visual/motor system can make it.

At this point, the computer completes the ballistics solution and starts to inject the azimuth gun lead angle order  $\lambda$  into the sight optical platform as shown in figure 2. The gunner sees the reticle moving off and trailing the target. Consequently, in an effort to get the center of the reticle back on to the target, the gunner adjusts the stick to move the turret faster in the opposite direction, which now moves the azimuth gun line ahead of the target. In other words, the computer is disturbing the sight line so it lags the target, and the gunner is countering the disturbance by commanding the gun line (and sight) to lead the target. This "dispute" over system control between the human operator and the computer continues until a steady state is reached (for this scenario only) where the gunner has the reticle back on the target and the computer has the gun line  $\theta_g$  leading the sight line  $\theta_s$  by an angle  $\lambda$ .

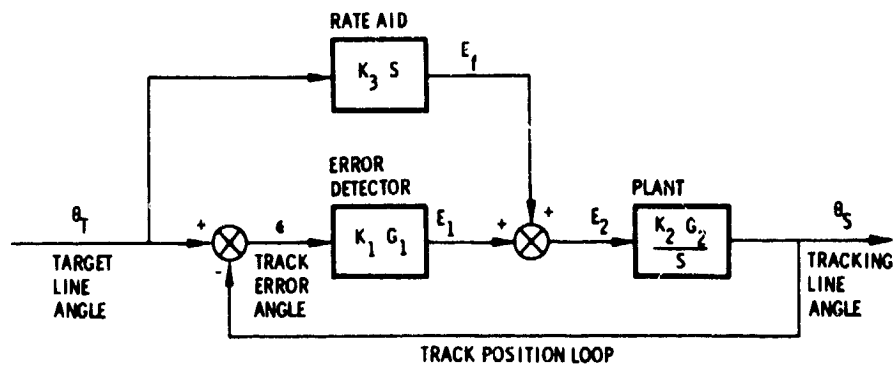
The human error sensor processes all of the target track data and the lead angle data. It can be seen that the whole system quickly degrades and approaches instability when the operator has to track a fast maneuvering target.

## DIRECTOR TYPE TRACKING SYSTEM

### Control Technique: Velocity-Feed-Forward

The design of the director type system depends heavily upon a control engineering technique called velocity-feed-forward. Sometimes this concept is briefly referred to as "rate-aid". The principle of "rate-aid" is illustrated generically in the block diagram in figure 3.

Given a position feedback loop, which is exactly what a tracking loop is, the objective is to reduce the track position error  $\epsilon$  to an acceptable level. This is usually done by raising the open loop gain ( $K_1K_2$ ), as long as loop stability is maintained. Velocity-feed-forward makes this possible because it is a function ( $K_3$  in figure 3) that is not inside the loop and therefore does not tend to degrade loop stability.



STEADY STATE ERROR FUNCTION	NO RATE AID	WITH RATE AID
$\left  \frac{\epsilon}{\theta_T} \right $	$\frac{1}{1 + K_1 K_2}$	$\frac{1 - K_2 K_3}{1 + K_1 K_2}$

Figure 3. Velocity-Feed-Forward Principle of Dynamic Error Reduction

If the target velocity  $\dot{\theta}_T$  is once again constant, say 0.5 radian/second, the plant input voltage  $E_2$  must be 5 Vdc in order to make  $\dot{\theta}_S = 1$  radian/second. Without velocity-feed-forward, the track error  $\epsilon$  must be a certain value in order to make  $E_2 = 5$  Vdc. The value of  $\epsilon$  is determined by the transfer function shown in figure 3 for no rate aid.

With the rate aid ( $K_3 S$ ) function scaled properly,  $E_2$  can be set to 5 Vdc by letting the rate aid output voltage  $E_f$  provide the 5 Vdc. Now the error detector voltage  $E_1$  and the track error  $\epsilon$  can go to zero. This relationship is shown in the figure 3 transfer function with rate aid.

#### Sharpshooter: The Manned Director-Type Tracking System

Referring once more to the basic weapon system shown in figure 1, the director type tracking system uses the relative motion relationship between the sight and radar azimuth axes and the turret axis and the velocity-feed-forward control technique to track and generate gun lead angles without either the operator/stick or the computer subsystems being inside the loop. A conceptual block diagram for the director tracking system is shown in figure 4. (To simplify the diagram, details such as D/A converters have been eliminated.)

In the figure 4 system, the radar subsystem provides range data to the computer for ballistics and is slaved to the sight so that  $\theta_A = \theta_S$  at all times. Note also in figure 4 that a rate gyro has been added as feedback around the sight optics platform. The sight line is inertially stabilized in space, and when the turret azimuth axis  $\theta_g$  moves under the sight azimuth axis (see figure 1), the sight line  $\theta_S$  will not move with  $\theta_g$ .

The major difference to note between the systems shown in figure 4 and figure 3 is that the track error sensor (in this case the operator) is not in cascade between the sight and the gun loops. As we shall see, the operator/stick subsystem has been ideally eliminated from the loop, even though the operator is still observing  $\epsilon$ , the tracking error, as seen through the sight reticle.

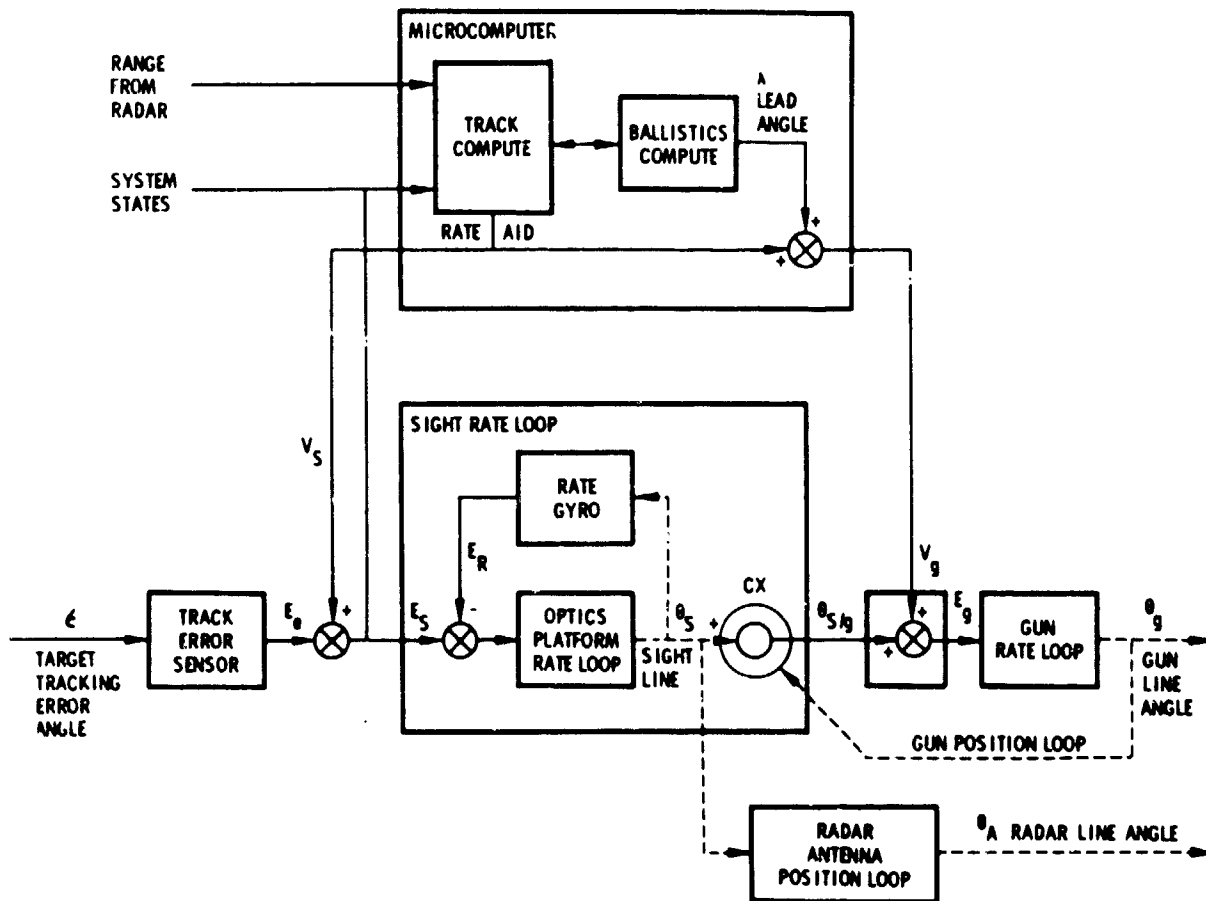


Figure 4. Sharpshooter Director-Type Track Loop - Conceptual Model

For purposes of discussion, consider again the target at constant velocity and range in order to simplify the explanation of how the manned director tracking system functions physically. Diagrams of the tracking sequence are presented in figure 5.

Assume the target is flying at a fixed altitude in a circular path (fixed range) at a constant angular velocity of 0.5 radians/second. At the center of the circle is the weapon system in figure 1 with the fire control system in figure 4. When the operator initiates tracking, the track error sensor (operator/stick) in figure 4 senses error  $\epsilon$  (difference between target and reticle functions) and enters a correction. This causes a stick output voltage to be applied to the gyro stabilized sight loop ( $E_s$ ). The



sight line ( $\theta_s$ ) moves ahead of the gun line ( $\theta_g$ ), causing this angular difference ( $\theta_{s/g}$ ) in the sight synchro transmitter (CX) to apply a voltage  $E_g$  to the gun rate loop. In order to make the gun line (turret) velocity  $\theta_g$  reach 0.5 radian/second, assume  $E_g = +5$  Vdc is required. When the sight line  $\theta_s$  has moved ahead of the gun line  $\theta_g$  such that the sight-with-respect-to-gun angle  $\theta_{s/g}$  is at the value to produce +5 Vdc at  $E_s$ , then the relative motion between the sight azimuth and turret azimuth axes stops. At this point, all three axes are rotating in space at 0.5 radian/second; the sight reticle is (depending upon operator dexterity) either on the target or lagging slightly at an angle  $c$ ; the relative position between the three lines is as shown in figure 5(a); and the operator is providing 5 Vdc at  $E_s$ .

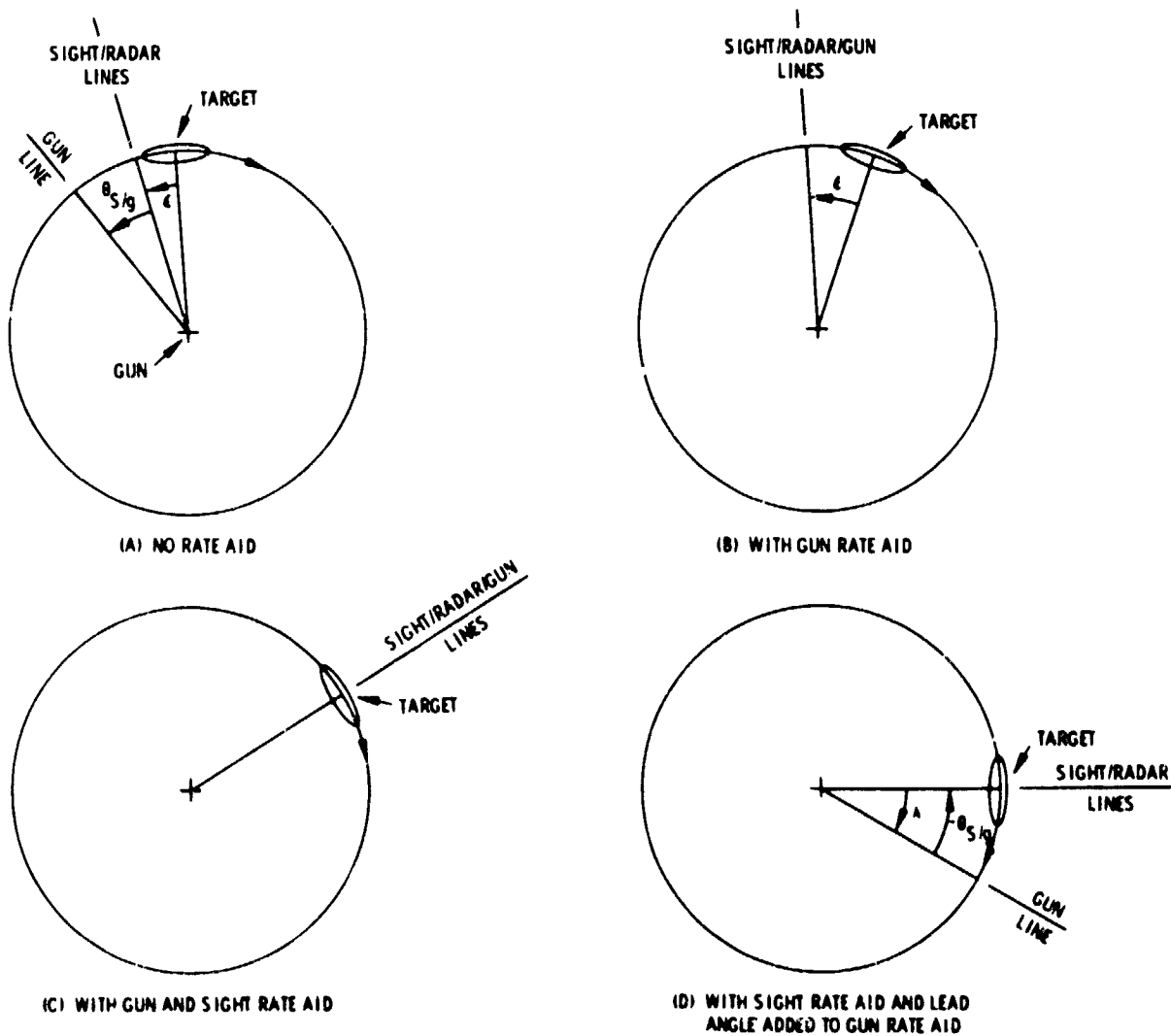


Figure 5. Tracking Operation Sequence (Azimuth) - Constant Velocity Target

Note, however, that the sight line ( $\theta_s$ ) and radar line ( $\theta_A$ ) are ahead of the gun line ( $\theta_g$ ). To achieve the zero lead angle, it is desirable to have gun line  $\theta_g$  coincident with lines  $\theta_s$  and  $\theta_A$ . This is achieved by the computer. By operating on the system state data (figure 4) in the tracking computation, the computer outputs the +5 Vdc required at  $E_g$  by raising the value of  $V_g$  in figure 4. Now the gun turret starts to accelerate under the sight, but the gyro in the sight senses this and holds the sight line  $\theta_s$  back on the target automatically.  $\theta_s/g$  reduces during this process to zero causing the synchro transmitter (CX) output voltage to become zero. At this point, the computer is providing the +5 Vdc at  $E_g$  to move the turret at 0.5 radian/second; the operator/stick (track error sensor) is still providing the +5 Vdc at  $E_s$  in response to observed  $\epsilon$  (note that rate gyro is moving in space and the output is -5 Vdc in response to turret velocity); and the relationship among the three lines is as shown in figure 5(b).

Now the computer outputs the +5 Vdc rate aid required at  $E_g$  by the rate gyro in order to eliminate the need for a tracking error  $\epsilon$ . So as  $V_g$  is raised to 5 Vdc, the reticle starts to move closer to the target,  $\epsilon$  goes to zero, and the error sensor stick output also goes to zero. With both rate aids applied, all three lines are coincident with the target line as shown in figure 5(c). The computer is now tracking and the human error sensor is merely observing the quality of the computer's track. If small corrections are required, the human supervisor can add corrective signals via the stick at the point  $E_e$  in figure 4.

Note that at this stage of operation, shown in figure 5(c), the operator is decoupled from the track loop and the computer is performing the continuous tracking function. The operator "communicates" with the computer via point  $E_e$  in figure 4. If the target is maneuvering, the operator adjusts the stick signal to correct track and the computer alters its target model to suit.

Still in control, the computer now determines the required lead angle  $\lambda$  via its ballistics computation. For example, it raises  $V_g$  from 5 Vdc to 7 Vdc in order to achieve "2 volts of lead angle" between the sight line  $\theta_s$  and the gun line  $\theta_g$ . Once again the gun turret accelerates under the sight and ahead of it because the rate gyro loop holds the sight line  $\theta_s$  on the target. This process continues until the situation shown in figure 5(d) reaches steady state. At this point the gun line  $\theta_g$  leads the sight line  $\theta_s$  by lead angle  $\lambda$ . This means  $\theta_s/g = -\lambda$  and the sight produces a negative CX signal from the sight of -2 Vdc which is summed with  $V_g = +7$  Vdc to produce the steady state +5 Vdc required to move the turret at 0.5 radian/second.

In contrast to the complex visual/motor tasks that must be performed for the disturbed-line-of-sight (DLOS) system, the operator does nothing to produce the lead angle in the director system. The human role is that of mentor, monitoring how well the computer performs its task and providing corrective refinements to the track operation as required.

In presenting this explanation, a sequence of discrete steps was described. In actual practice, the operation is continuous and all functions change simultaneously. The concept of the operator as a tracking

error detector should be mentioned. The tracking error sensor could be: (1) an RF sensor if a radar receiver detector is used, (2) an electro-optical sensor if an IR or TV video tracker is used, or (3) a biological receiver detector if an operator is used. In figure 4, the error sensor could be any one of these. The Sharpshooter no. in production uses the radar in one tracking mode and the operator in the optical tracking mode.

#### MICROPROCESSOR IMPROVES MAINTAINABILITY

All control system functions shown in figure 4 are performed within a microprocessor controller. The microcontroller communicates directly with the microcomputer and forms a powerful distributed processing system. Taking advantage of this capability provides system diagnostics, enhances maintainability, and reduces human-induced errors.

"...Human error accounts for at least 50% (underline added) of the failures of major [military] systems."\* "The increasingly complicated nature of modern military systems together with shortages of qualified military personnel suggest that human-induced errors both in operation and maintenance of systems will increase unless more attention is given to this problem in the design and development phases of the acquisition process." "The problem of human-induced failures may very well become worse. Attendant to the increasingly complicated nature of systems are the lower education and aptitude levels of personnel now entering the services, the shortages and high turnover rate of experienced personnel, which lead to very low overall experience levels, and the effect of greater use of complex/sophisticated automatic checkout and built-in test equipment [that is difficult for the maintainer to use]."

One way of maintaining increasingly complex equipment while the level of skills of technicians decreases is to provide equipment for fault location and diagnosis that does not require highly skilled operators. The microprocessor that allows for the increased accuracy of the system described above also provides built-in test and diagnostic functions for system maintenance that would not be possible otherwise.

Both static and dynamic tests are conducted and, in many instances, faults are isolated to the circuit board level. Fault indications permit the operator to deal directly with some problems and refer maintenance personnel to areas the operator is not equipped to handle.

The built-in test equipment (BITE) philosophy automates BITE functions to the greatest degree possible minimizing operator participation in the test function. The computational capabilities of the microprocessor are used as much as possible to test the system rapidly. Tests are made to as basic a level as possible, and failure indications are correlated with the required maintenance test support equipment. This makes it unnecessary for test personnel to have to decide which tests to run. Computer automated static and dynamic tests are performed in addition to operational tests of the system in normal operating modes.

\*This quotation and the others in this paragraph are all taken from Reference 8, p. 27.

During static tests power supply voltages and radar signals are sampled and compared with acceptable levels stored in memory. Coded error data are displayed on the control/display panel.

A basic operability test of the antenna and gun/turret servos is conducted in a similar way. More detailed diagnostic tests of drive signals to the optical sight, radar antenna, and weapon servo loops are also made in various combinations to ensure the proper functioning of those subsystems.

Through these aids the condition of the system can be assessed rapidly by relatively unskilled personnel. When maintenance action is required, the diagnostic capability provides enough guidance for a technician who is not highly skilled to be able to repair the system quickly.

#### CONCLUDING REMARKS

The improvements made in the manned-director type fire control system show large gains in human factors aspects as well as in system accuracy. Complex visual/motor tasks usually performed by the operator are now reduced to functions executed by a microprocessor, thus freeing the operator to oversee system operation. The microprocessor can also be programmed to test the system at regular intervals, which allows early location and diagnosis of faults. The built-in test feature enables maintenance personnel to circumvent repetitious checkout and troubleshooting procedures and repair the equipment using programmed instructions commensurate with their skills.

Future efforts in this area will be directed toward adaptive operator control filters, refinements in the built-in test programs, and toward adopting the console to increase the operator's effectiveness as supervisor of system performance.

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