

Electro-Optical Tracking Systems Considerations

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ABSTRACT

This tutorial paper discusses the performance requirements and design parameters for Electro-Optical Tracking Systems. Descriptions of tracking systems for range instrumentation are discussed. The relationships between the performance requirements, target characteristics and the system optical sensors, tracking algorithms, pedestal dynamics, servo control loops, and ancillary equipment are examined. The design considerations related to the operator interfaces are also discussed.

1. INTRODUCTION

An Electro-Optical Tracking System can be viewed as having certain essential elements which can be structured in a variety of configurations to meet specific mission requirements. As a minimum, a tracking system contains: A sensor package for detection of the target's radiated energy, a positioning system to follow the target trajectory, and a method of commanding the positioning system.

E-O tracking systems can also contain other instrumentation, such as laser rangefinders, laser radars, and range-only radars, which complement the system architecture in providing precise spatial position data. Figure 1 is a picture of the Super Radot high-precision Tracking System used in the study of reentry vehicle phenomenology [1]. The Super Radot System provides long-range position data using low light level video sensors with data recorded on videotape for post-mission data reduction. An intensified silicon intensified video camera (ISIT) is interfaced to a 60 cm aperture 600/1200 cm focal length lens. This sensor optics combination provides target ranges in excess of 800 km slant range acquisition to impact. Angular tracking rates are one radian/sec with reduced data accuracies of 4-7 microradians in both axes.

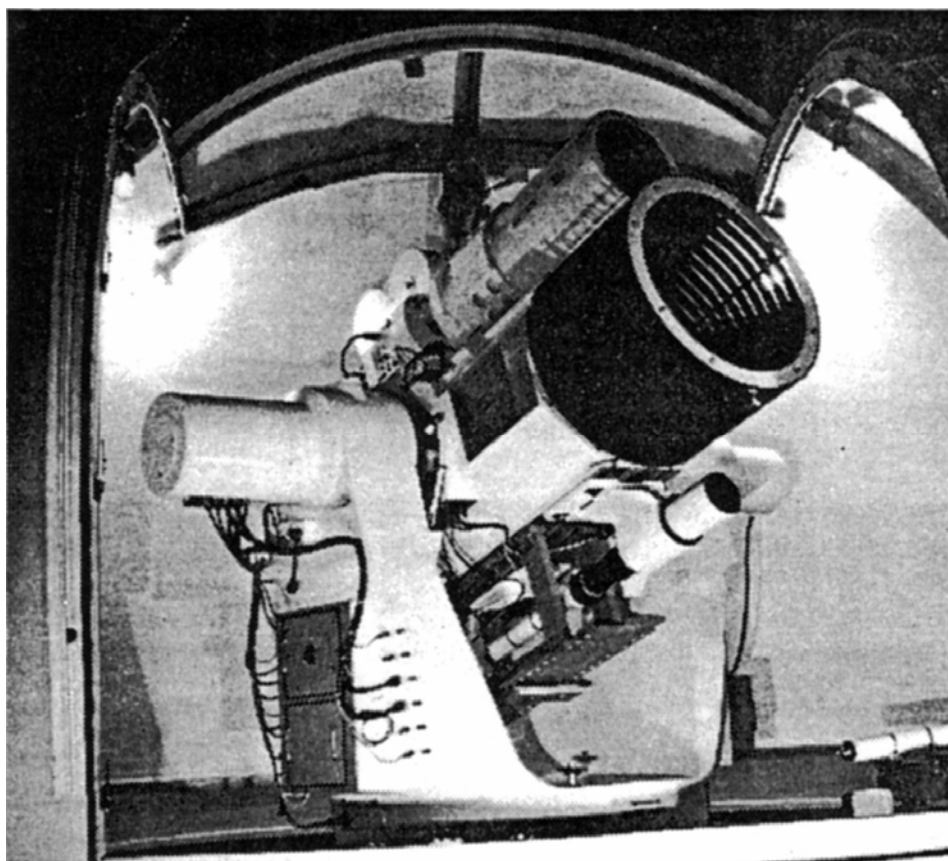


Figure 1. Super Radot Tracking System

Figure 2 is a block diagram of a fully complemented E-O tracking system.

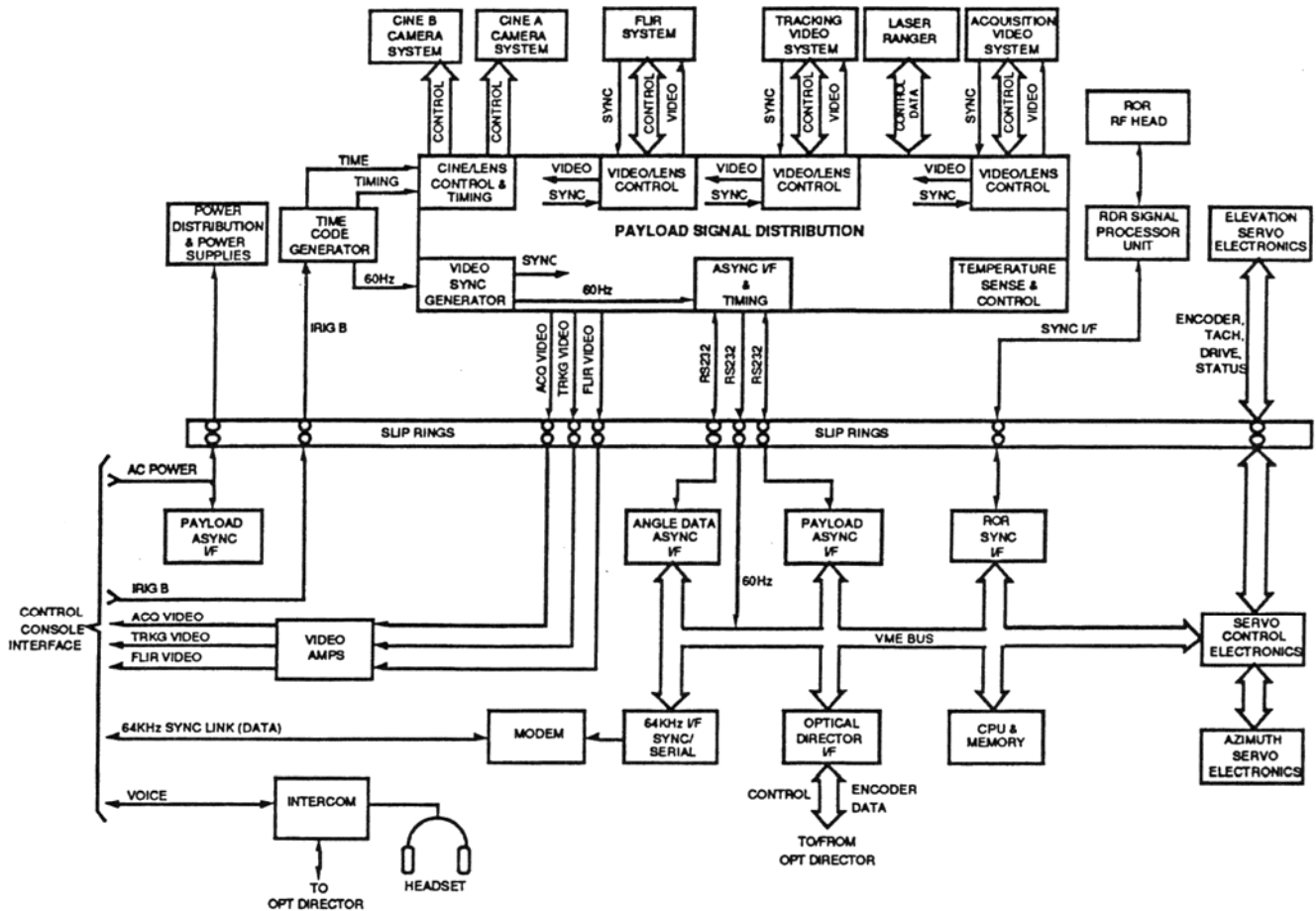


Figure 2. Tracking System Block Diagram

The numerous applications for E-O tracking systems can be divided into five major categories as follows:

- Real time surveillance
- Laser designation systems
- Range instrumentation
- Homing missile guidance
- Weapon fire control

The operational requirements on an E-O tracking system are:

- Target detection
- Data collection
- Target autotrack
- Real-time data reduction

The primary performance factors are:

- Target characteristics
- Tracking accuracy
- Data resolution
- Acquisition range
- Metric accuracy

The target characteristics which must be considered in the tracking system are:

- Size
- Background radiance
- Range
- Target radiance
- Dynamics

Figure 3 shows the relationship between the target and environmental parameters.

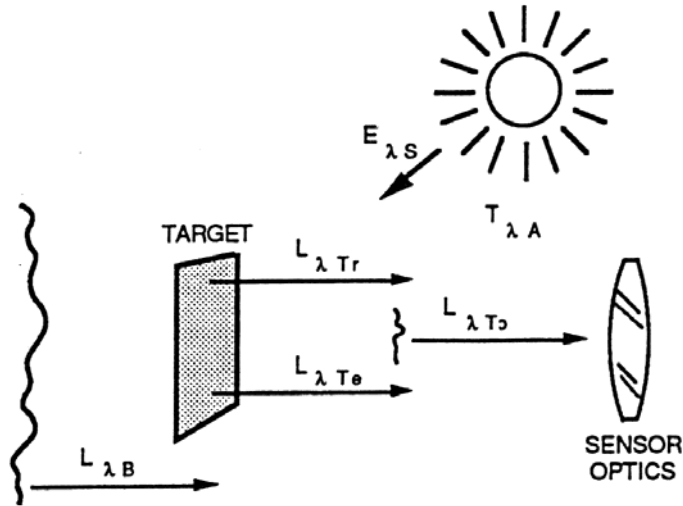


Figure 3. Relationship Between Target and Environmental Parameters

The target contrast, C_T , is defined as

$$C_T = \frac{L_{TS} - L_B}{L_{TS} + L_B}$$

where

$L_{\lambda B}$	background spectral radiance
$L_{\lambda Tb}$	background contribution to target
$L_{\lambda S}$	incident spectral irradiance on target
$L_{\lambda Tr}$	reflected radiance contribution of target
$L_{\lambda Te}$	emitted radiance contribution of target
$L_{\lambda A}$	atmospheric transmission

The following sections of the paper present a tutorial on the subsystem design factors which must be considered in configuring the tracking system.

2. DESIGN REQUIREMENTS

Subsystem Design Requirements

The major subsystems in the E-O tracking system are: (1) the sensor, (2) the gimbal system, (3) the video tracker, and (4) the gimbal control system. The design of each of these subsystems must take into account the operational mode requirements, the environment, the target characteristics, the performance requirements, the physical and cost constraints, and the data collection requirements.

Sensor Subsystem

The sensor subsystem consists of the detector array, the optics and the sensor electronics. Imaging sensors are used in most precision tracking applications, but single element and quadrant detector configurations are often used in missile guidance applications. Figure 4 shows the relationship between the target parameters, the environment, the optical parameters, the detector parameters, and the target voltage signal-to-noise ratio produced by the sensor. The detector and optics parameters must be selected to provide an adequate SNR to permit target detection and automatic tracking. The key sensor parameters are the optics aperture, the optical focal length, the detector size and the detector and electronics noise and offset parameters. The sensor spectral band must be selected to permit operation in the required environment. The sensor dynamic range must permit adequate target SNR over the range of target and background radiance conditions. The sensor time response and update rate must be designed in conjunction with the track loop dynamics to assure adequate target position data (in the sensor field of view) is available to the tracker and the track loop to meet the tracking system pointing error requirements.

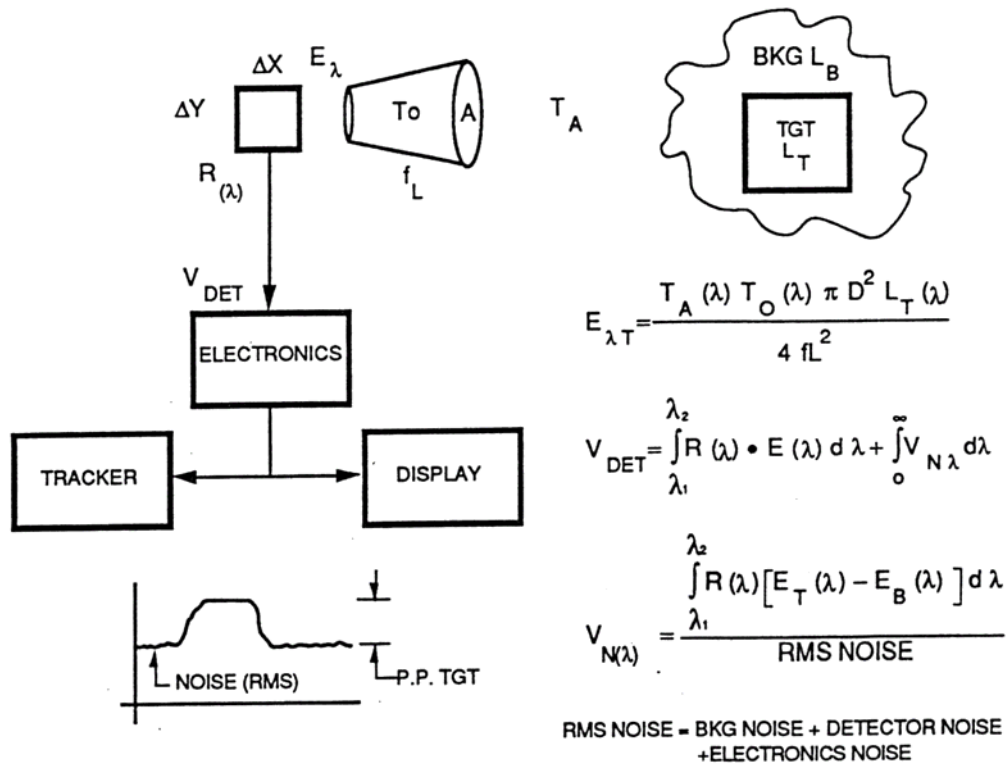


Figure 4. Target/Sensor System Model

where

L_T	Target radiance	$E(\lambda)$	Radiance on detector
L_B	Background radiance	ΔX	Detector X dimension
T_A	Atmosphere transmission	ΔY	Detector Y dimension
A	Optics collecting area	$R(\lambda)$	Detector spectral responsivity
T_O	Optics transmission	V_{DET}	Detector output voltage
f_L	Optics focal length	$V_{N(\lambda)}$	Detector spectral noise characteristics

Important sensor characteristics are summarized as follows:

- Spectral range
- Resolution
- Bandwidth
- Lag
- Linearity
- Blooming
- Transfer Characteristics
- Noise
- Shading
- Blemishes
- Sensitivity

The following is a summary of key parameters in determining the optical system requirements:

- Required range
- Target size at minimum/maximum range
- Target contrast
- Pointing accuracies
- Atmospheric
- Region of spectral interest
- Optical distortion
- Axis shift for zoom lens

Gimbal Configuration

The following factors require consideration when determining the pedestal configuration.

- Sensor Configuration
- Velocity/Acceleration
 - Maximum
 - Minimum
- Wind Loading
- Base Motion
- Angular Travel Azimuth and Elevation
- Resonant Frequency
- Pedestal Accuracy
 - Backlash
 - Static Repeatability
 - True Position Accuracy

The most common configuration is the elevation over azimuth yoke type with the payload mounted between the elevation structure or outboard (reference Figure 5).

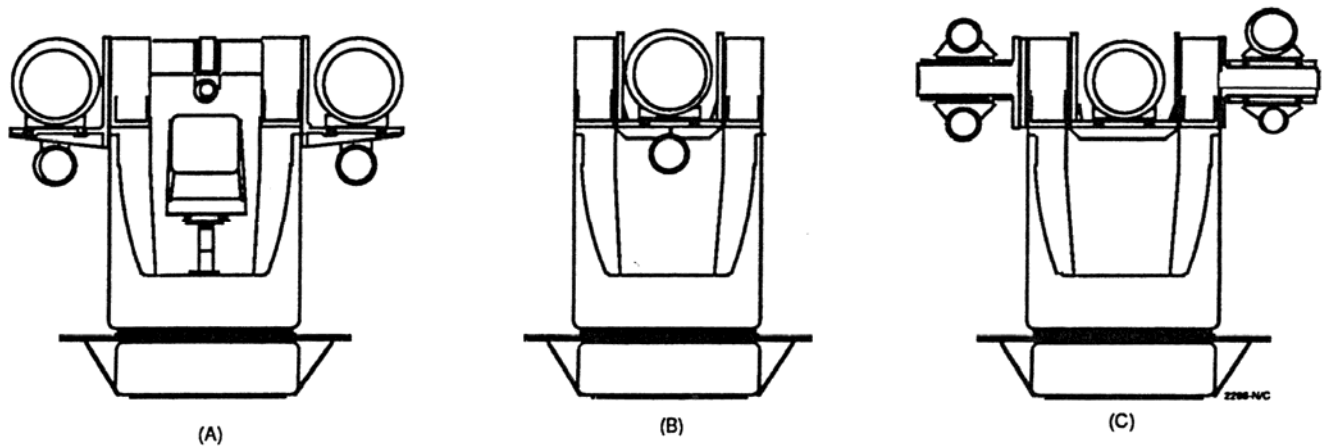


Figure 5. Gimbal Mounting Configurations

Other configurations utilize multi-axis stabilization to remove the effects of mount motion. Mirror mount systems permit fixed payloads with the image transferred to the sensor by a moving mirror as shown in Figure 6.

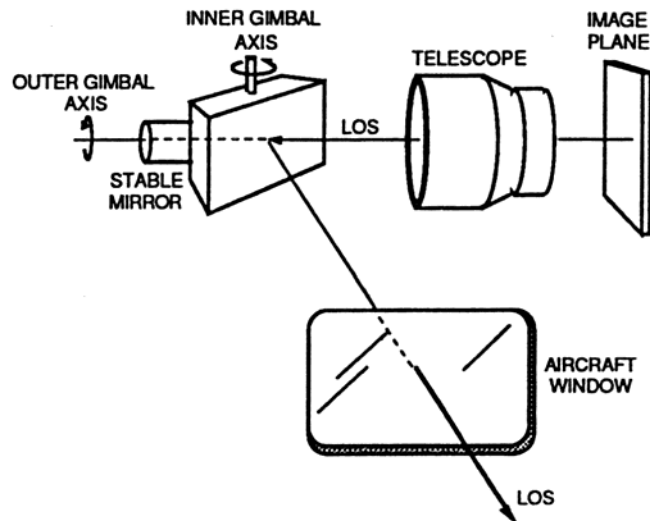


Figure 6. Mirror Mount System

Gimbal Control System Description

The Gimbal control system positions the sensor package in response to commands from three control loops. Figure 7 shows a block diagram for the gimbal control system. Typically, the gimbal control system has a tachometer or inertial rate loop which accepts rate commands from (1) an operator, (2) a position loop, or (3) a video autotrack loop. The command source is determined by the mode of operation.

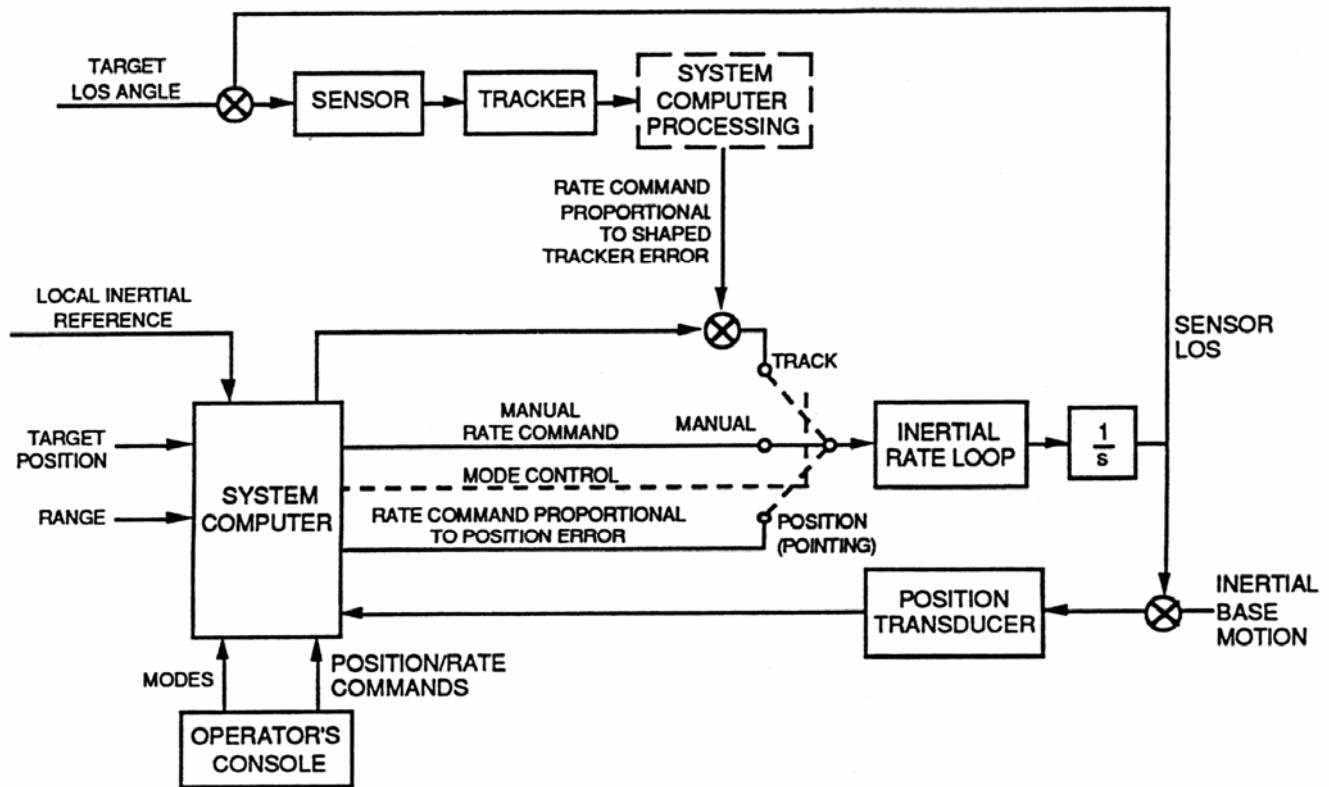


Figure 7. Gimbal Control System

In the Manual system, the operator positions the gimbal through a positional control (joystick) following the target's motion on a display or viewing through an optical sight. The limitation of manual systems is the operator's inability to respond to target dynamics.

In a Designate system, the target's trajectory is determined from an external source such as radar or a prior knowledge of the target trajectory. This data is used to drive the gimbal's position encoders to known positions. The accuracy of this mode is determined by the tracking accuracies of the external input or the stored trajectory data.

In an Autoposition system, initial acquisition is accomplished by operator identification and selection of the target. The operator then initiates the autopositioning or autotrack mode and the tracking processor positions the gimbal based on the calculated target position.

Precise measurement of the angular portion of the line of sight is a requirement in many range instrumentation applications. The measurement accuracy is a function of the pickoff resolution and linearity, and the alignment of the pickoff to the gimbal axes. The most common types of transducers [2] are listed in Table 1, showing their relative accuracies.

Table 1. Common Transducers and Their Accuracies

Type Transducer	Accuracy Arc Sec
Optical Encoders	0.5-1
Inductosyns	1 - 2
Multiple Speed Synchro/Resolvers	7
High Accuracy Synchro/Resolvers	20
Standard Synchro/Resolvers	180 - 480
Potentiometers	480

Evaluation factors when selecting an angle transducer are:

- Reliability
- Performance
 - Repeatability
 - Accuracy
- Stability
- Static and Dynamic Mechanical Load
- Environmental Considerations

TYPE I AND II POSITIONING SYSTEMS

Gimbal systems are typically designated Type I or Type II depending on the tracking system requirement. A Type I servo is defined as having one integrator in the open loop characteristic, while a Type II system contains two. The choice of servo type is determined by the allowable error characteristics of the system. Type I servos yield a constant error for a constant angular rate input. Type II servos yield a constant error for a constant angular acceleration input.

The total dynamic tracking error, e_t , for a Type I or II servo system is approximated by:

$$e_t = e_v + e_a$$

where e_v is the velocity error, and e_a is the acceleration error, defined as:

$$e_v = \frac{|\dot{\theta}_{\max}|}{K_v} \qquad e_a = \frac{|\ddot{\theta}_{\max}|}{K_a}$$

where

- $\dot{\theta}$ Target maximum velocity
- $\ddot{\theta}$ Target maximum acceleration
- K_v Velocity error constant
- K_a Acceleration error constant

For a Type II system, K_v is typically on the order of 600-1000 reducing this term to zero (0).

TRACKER SUBSYSTEM

The class of tracker implemented for a E-O tracking is referred to as an imaging tracker. An imaging tracker is one which uses a single sensor producing video signals by means of a linear scan. Figure 8 schematically represents a tracker [3].

The transfer function of the TV Tracker Output, $G(s)$, is expressed by:

$$G(s) = \frac{1 - e^{-\frac{s}{60}}}{s}$$

The above equation provides the basis for determining tracker performance when integrated into an electro-optical tracking system.

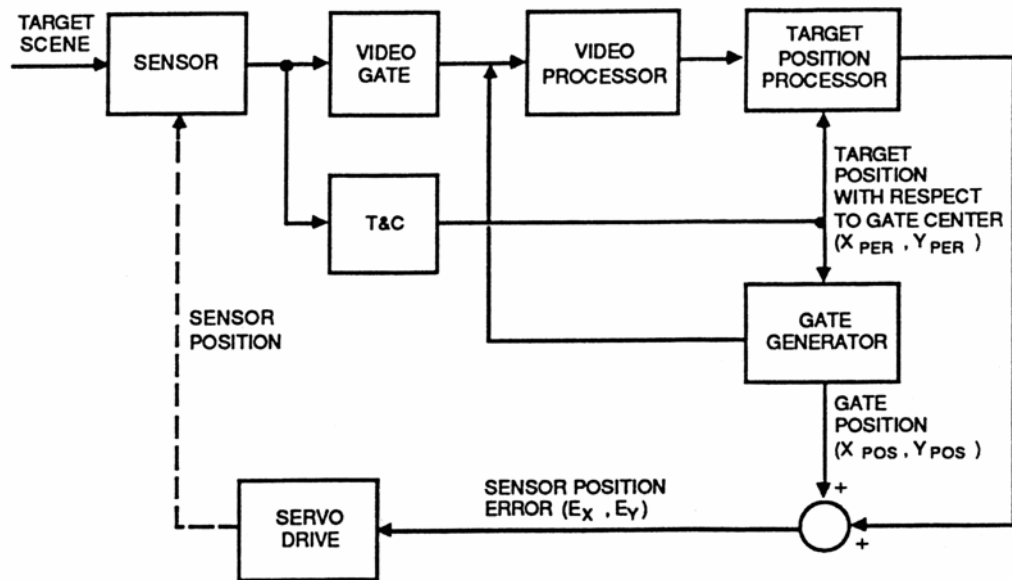


Figure 8. Tracker Block Diagram

In conventional 525 line TV systems, approximately 30×10^4 picture elements per frame are processed in the construction of a TV scene. Horizontal and vertical scans are controlled by internal clocks; whereby, the horizontal (“X”) and vertical (“Y”) coordinates of any picture element are known within the time domain. By gating the video signal and synchronizing the tracker electronics to the video signal, the image position can be determined through time analysis of the video in relation to the TV horizontal and vertical sync signals. This time correlation determines image (target) position signals which are proportional to the deviation of the object from the optical axis.

Tracking Techniques

Various algorithms are available for generating the system tracking errors. In analyzing the requirements for E-O tracking systems, a wide range of target characteristics can be anticipated, such as low contrast objects, extended sources and targets in complex scenes. Table 2 provides a match of target classes to tracking algorithms.

Table 2. Algorithm Versus Target/Background

Target Background	Aircraft Sky	Aircraft Terrain	Ship Sky/Sea	Ship Shore	Vehicles on Land	Terrain Features	Missile	Laser Designator	Reentry Vehicles	Star (Point Source)
Edge	0	-	X	0	-	-	X	-	X	
Centroid	X	0	X	0	0	X	X	X	X	X
Correlation	X	X	X	X	X	X	X	0	X	0

NOTE: Algorithm selection can be influenced by sensor spectral response CCTV, SDA, FLIR
 X = Typical application
 0 = Possible application
 - = Not a Typical application

Three classes of tracking algorithms – edge, centroid and correlation – will be discussed.

Edge Tracking

An edge tracker seeks the first point on the selected target of interest occurring within the gate and maintains track on that point.

The gate is used to reject a major portion of the target background and allow processing of only the selected track point area. Thus, the gate of the edge tracker may be used to reject unwanted background signals.

When the first video pulse from the selected target occurs, the horizontal and vertical target position information is stored and used to compute the error signals for the servo system (reference Figure 9).

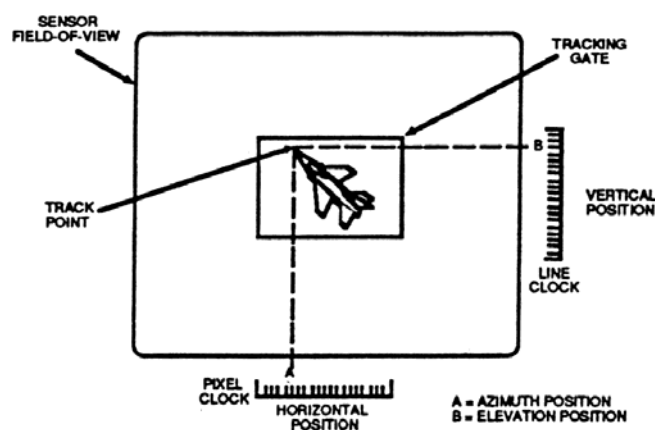


Figure 9. Edge Track

An Edge tracker can be configured to track various edges of the target as shown in Figure 10. This capability allows tracking of extended targets (i.e., missile, weapon stores separation) where centroid tracking would be biased off from the track point of interest. One inherent disadvantage of edge tracking is any random noise will cause a disruption of track since only a single data point is being used for position determination.

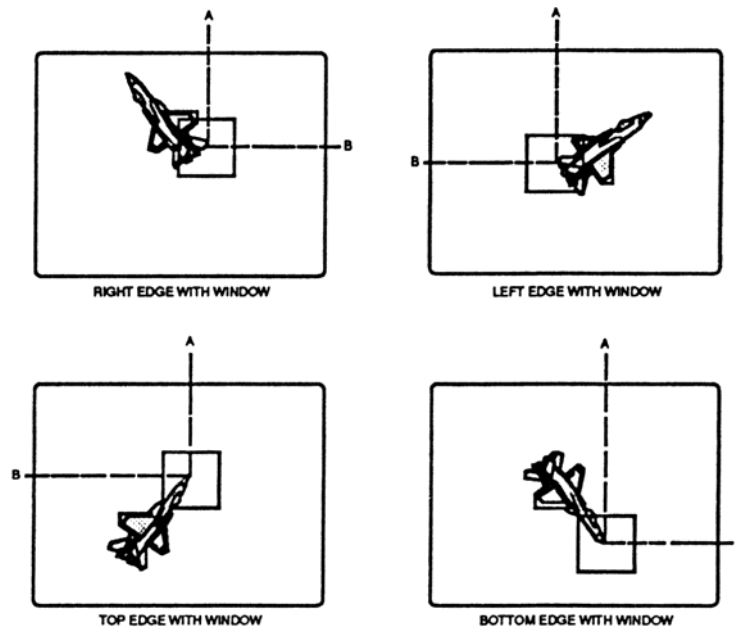


Figure 10. Selectable Edge

Centroid Tracking

Many Centroid algorithms are available for generating the tracking error signal (X_{Cent} , Y_{Cent}). The following is an overview of various Centroid algorithms.

$\frac{A+B}{2}$ Centroid Algorithm

An extension of the basic edge tracker is the $\frac{A+B}{2}$ Centroid algorithm. In this algorithm the top, left, right and bottom edges of the target are determined. The tracking point coordinates are then taken as the midpoints between the opposite edges.

$$X_{Cent} = \frac{X_{RE} + X_{LE}}{2} \quad Y_{Cent} = \frac{Y_{BE} + Y_{TE}}{2} \quad \text{where} \quad \begin{array}{ll} X_{RE} = \text{Right Edge} & Y_{TE} = \text{Top Edge} \\ X_{LE} = \text{Left Edge} & Y_{BE} = \text{Bottom Edge} \end{array}$$

While the $\frac{A+B}{2}$ algorithm provides the ability to track an interior point on a target, the algorithm has some basic limitations. Error calculations are determined by only two data points in each axis. This makes the error signals extremely dependent on spatial equalization, variations in video scene and noise content. Under low contrast conditions (specular target), the optimum shape for this algorithm would be a symmetrical target (i.e., laser spot, star, or point source).

Integration Algorithms

Area Balance

The Area Balance algorithm seeks to balance the target area located within the target on opposite sides of the system null point. The major limitation is its dependence of tracker error characteristics upon target size and shape. The optimum shape for this algorithm would be a symmetrical target (i.e., laser spot, star, or point source).

Center of Mass

The true centroid of a two-dimensional object corresponds to its center of mass. By utilizing the x-y television scan and a high-speed horizontal clock, we may break each television frame into a matrix.

The mass of the target is defined as the summation of all of the elemental masses (m)

$$M = m_1 + m_2 + \dots + m_n = \sum_{k=1}^n m_k$$

in a corresponding manner, the moments of mass in the x and y axis may be determined by

$$M_x = x_1 m_1 + x_2 m_2 + \dots + x_n m_n = \sum_{k=1}^n x_k m_k$$

$$M_y = y_1 m_1 + y_2 m_2 + \dots + y_n m_n = \sum_{k=1}^n y_k m_k$$

from the above, the coordinate x,y of the center of mass may be defined as:

$$\bar{x} = \frac{\sum x_k m_k}{\sum m_k} \quad \bar{y} = \frac{\sum y_k m_k}{\sum m_k}$$

Figure 11 represents the Center-of-Mass algorithm.

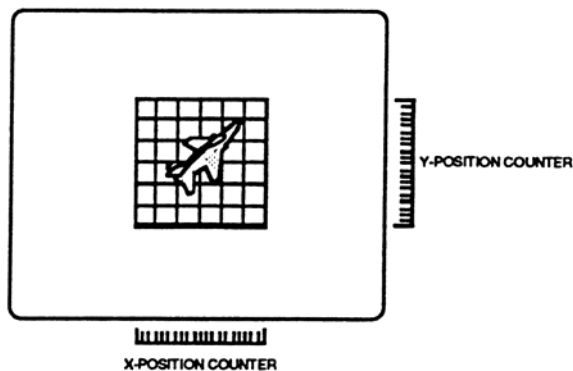


Figure 11. Center-of-Mass Algorithm

The Center-of-Mass algorithm is as follows:

$$\frac{\sum_{i=0}^m X_i}{\sum_{j=0}^n N_j} = X_{PE} \text{ Centroid} + \text{Remainder} \qquad \frac{\sum_{i=0}^m Y_i}{\sum_{j=0}^n N_j} = Y_{PE} \text{ Centroid} + \text{Remainder}$$

where

- X_i X-position of target pixel *I* above threshold
- Y_i Y-position of target pixel *I* above threshold
- m, n Total number of data points (pixels above threshold)

Intensity Centroid

An extension of the Center-of-Mass algorithm is the Intensity Centroid algorithm. Here, the target data is processed using the intensity weighting of the individual pixels within the tracking gate. With this algorithm positional resolutions of 1/64 of a pixel are obtained. The target intensity centroid can be represented by:

$$X \text{ Intensity Centroid} = \frac{\sum_{i=0}^m I_i X_i}{\sum_{j=0}^n I_j} \qquad Y \text{ Intensity Centroid} = \frac{\sum_{i=0}^m I_i Y_i}{\sum_{j=0}^n I_j}$$

where

- I_i = pixel intensity value (0-255)
- X_i = X position of the target
- Y_i = Y position of the target
- n,m = Total number of pixels

Correlation Tracking

Correlation algorithms measure the positional difference between a reference image which contains the target signature and a search area within which the target signature is now contained. The advantage of the correlation algorithm over edge and centroid algorithms is its ability to track a particular feature or a particular target in a group of targets.

Typically, correlation trackers use several frames of video data and process them simultaneously. By summing several frames together, the effects of random noise are minimized and the target is effectively enhanced. Obviously, frame-to-frame summation is advantageous when low signal-to-noise ratio conditions are encountered.

A frame-to-frame correlation cannot only reduce the effects of noise-by-frame summation, but also compares each new frame of data-to-data stored in memory for a match in the two data frames. When a match is found, the output error signals describe the displacement of the most recent frame to the one stored in memory.

The correlation between two video images in the analog domain can be represented by

$$C_R(\tau) = \int_{-\frac{T_0}{2}}^{+\frac{T_0}{2}} V_1(t) V_2(t + \tau) dt$$

where

- $C_R(\tau)$ Correlation between V_1 and V_2
 $V_1(t)$ Original signal at time t
 $V_2(t+\tau)$ A signal shifted in time by $(t+\tau)$

The correlation process can be viewed as a multiplication, timeshift and integration process.

In the digital domain, the correlation function takes the form

$$C_R(m) = \sum_{k=-\infty}^{\infty} V_1(k) V_2(k + m)$$

where $k = t$ and $m = \tau$ from the previous discussion.

Considerations for the correlation processor are re- and post-processing of the data to minimize the effects of quantization, variations in target size, attitude and contrast.

Thresholding Algorithm

In our previous discussion of tracking algorithms, the techniques for transforming a continuous-time varying video signal into a discrete format suitable for processing were omitted. The subsequent paragraph describes a threshold algorithm implementation for converting the composite video signal into a discrete (1,0) signal for processing.

The threshold level, V_{th} , can be determined in the following manner:

$$V_{th} = (V_{peak} - V_{ave})N + V_{ave}$$

where

- N Varies between 0.1 and 0.9
 V_{ave} Average video level in the gate
 V_{peak} Peak video level

In order to determine V_{peak} and V_{ave} , several factors must be taken into account. First, V_{ave} depends upon the area of the gate for a linear response with small and large gate sizes.

In this manner, a larger gate has a faster response time than a smaller gate.

However, it is advantageous to allow only small frame-to-frame variations in V_{th} .

Therefore, the final V_{th} for the Automatic Threshold becomes:

$$V_{th} = N (V_{peak} = V_{ave}) + V_{ave}^{-t/RC}$$

where R is a function of gate area and C has a constant value.

Figure 12 is a functional block diagram of the threshold processor.

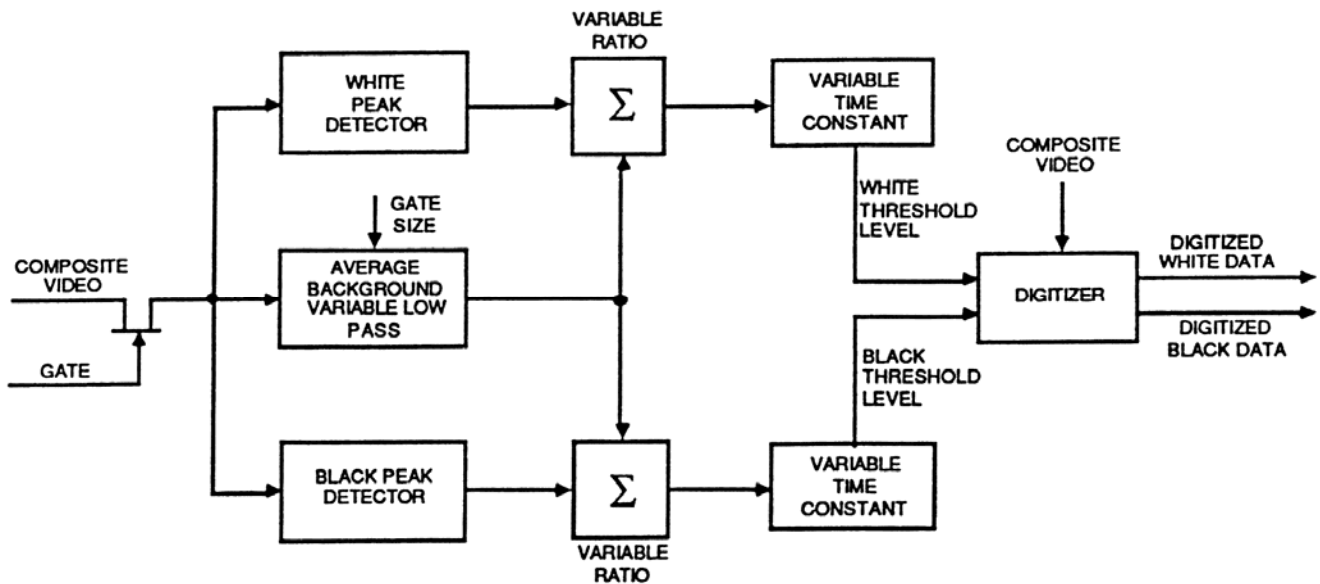


Figure 12. Threshold Processor

ANCILLARY EQUIPMENT

Ancillary equipment are those subsystems, when integrated into the basic E-O tracking system, enhance the system's ability to gather increased data about the target and store this data in an easily retrievable format.

Laser Ranging System

Integration of a Laser Rangefinder (LRF) into an E-O tracking system provides a high-accuracy, single-station solution in determining a target's spatial position. The LRF can replace the triangulation method for position determination or a radar system which has poor positional accuracies.

With the relatively large number of laser rangefinder systems available, important considerations should be given to the nature of the mission. Several of the more important considerations are as follows:

- Target reflectivity
- Laser output capability
- Atmospheric conditions
- Receiver sensitivity
- System size and weight constraints
- Measurement speed
- Range accuracy
- Operational wavelength
- System safety

Data Insertion

These systems provide a method of encoding mission parameters such as time, position, range, and gimbal angles on either video or film format for post-mission data reduction. A major problem encountered with today's range requirements is to provide a method of recording and reducing mission data in a cost-effective, time-efficient way. In the past, data reduction relied primarily on cine data for mission performance analyses and was extremely manpower intensive and time-consuming. With the coming of age of video as a prime source of mission data archiving, video data insertion and retrieval systems have found widespread use. With this approach, all pertinent mission data can be extracted for a specified frame of video with no timing ambiguities or complexities which result when event correlating between different recording media.

Range-Only-Radar (ROR)

Range-only-radar allows the tracking system a method of ranging and tracking targets outside the visible range of the E-O system or when the target is observed by atmospheric conditions. In this mode, the gimbal is placed in the directed position mode and slaved to the radar's positional data. Depending on beam width and the radar's encoder resolution/accuracies, varying degrees of tracking accuracy can be realized.

DISPLAY SYSTEM

The problem of interfacing the display system to the observer must be addressed far more critically than other hardware areas since it is the last interface in the system and introduces the human into the system as a decisions port.

Display system selection requires the same careful analysis of performance parameters as the sensor system and should be based on a thorough knowledge of the type and accuracy of information required. Summary of display system parameters:

- Brightness
- Contrast
- Resolution
- Distortion
- Accuracy
- Size

Display system performance requirements are dictated by the human operator and the nature of the task. For E-O tracking systems, this task can be divided into four categories: detection, orientation, recognition, and identification. Factors which effect accomplishing these tasks [4] are:

- Angular Threshold of the Eye (Visual Accuracy)
- Visual Search Time
- Line Resolution Requirements
- Image Contrast
- Image Complexity

Angular Threshold of the eye is the ability to resolve two adjacent objects. Under ideal conditions, the angular threshold is better than 1 arc minute. For a complex image, a target must subtend 6-17 minutes of arc for acquisition and recognition to have a probability of success of 95 percent or greater.

Visual Search Time is the time required to scan the particular display area and is affected by the eye's fixation time – typically 0.3 second – and the overall angular size of display relative to the observer.

Line Resolution is the ability of the observer to separate two adjacent objects. For most display systems, the system resolution is the limiting factor, not the observer.

Image Contrast is the difference between bright and dark regions on the display. Contrast ratio, C_R , can be expressed in two ways:

$$C_R = \frac{B_2 - B_1}{B_1} \quad C_R = \frac{B_2}{B_1} \quad \text{where } B_2 > B_1$$

Image Complexity. In the case of a complex image, the eye does not adapt to any single intensity level but to the average, depending on the gray level content. As the observer scans the image, the adaptation level fluctuates about this average. For any one event in a complex image, the eye can detect a range of one to two dozen intensity (gray) levels. For a uniform background scene, an observer can discern an object with contrast ratio of 2-3 percent.

Another factor is the orientation of the display to the operator. The display should be situated so the visual axis of the operator is perpendicular to the display surface at its center, with a nominal viewing distance of 14 to 18 inches. This configuration minimizes operator fatigue and provides the optimum viewing angle for interpreting the display.

POSITIONAL CONTROLS

This section discusses the ergonomic factors for consideration in predicting the performance of an operator in a positioning loop. The human operator in the position loop can be defined by two response parameters: a neuromuscular time display of 0.17 seconds, and a phase lag with a time constant of 0.1 second [5]. This response can be represented by:

$$\text{Operator Response} = \frac{e^{-0.17s}}{(1 + 0.1s)}$$

and allows estimation of the total loop response.

The three types of positional controls for tracking system applications are: Force (isometric), Displacement, and Trackball. The performance factors of interest are:

- Response
- Resolution
- Size
- Accuracy
- Environmental

Positional controls can also be classified by order [5]. A zero-order control would be one where there is a one-to-one correspondence in input stimulus to motion in the scene. The 2-axis joystick incorporating single-turn potentiometers is a zero-order control. The 2-axis trackball is a zero-order representation of a multiturn potentiometer.

With a 2-axis joystick, resolution is proportional to size, the larger the movement the greater the resolution. With the trackball, increased resolution is achieved by the number of revolutions at a sacrifice in speed.

A first-order control system can be obtained by placing a control element (integrator) in the loop to produce a rate output. With a rate output, resolution is no longer a function of the control size and a smaller control (joystick) can be used. Common to first-order systems is a return to null with release of the control.

Force (Isometric) Joystick can be viewed as a non-moving control to which an operator applies a force. The resolution of these devices is established by the smallest incremental force the operator can apply. The advantages an isometric control has over a 2-axis joystick or trackball is small size dictated by the operator's hand or finger size, shorter response time, and improved resolution. Isometric controls are used for environmental conditions where shock and vibration are a concern.

Other Ergonomic Considerations

While the display system and positional controls are of prime importance in determining operator performance, other factors such as control panel layout, control identification, and lighting also influence operator response and are critical to overall performance.

SUMMARY

E-O tracking systems usually consist of an imaging sensor, gimbal assembly, video tracker and control system which acquires and maintains a selected target in the sensor field-of-view. Type I and Type II track loops employing centroid and correlation trackers are very mature and are used to provide metric and imagery data for a wide variety of applications ranging from laser designation to SDI test instrumentation. The principal areas of development in tracking systems are (1) video tracker algorithms and hardware implementations, (2) sensor fusion, and (3) applications of modern control techniques such as Kalman filtering.

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