Design and Construction of the Detection Unit in Laser Tracking System

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Abstract

We present the design and construction evidence of a laser tracking system. This system is consists of an optical part representing by two reflective elements, optoelectronic part(quadrant photodiode detector), and mechanical part The dimensions of these parts as well as the focal length and the radius of tracking region, is achieved.

ملخص

في هذا البحث تم تصميم وبناء وحدة كشف لمنظومة تتبع ليزيرية. تتكون من عدة أجزاء: منها جزء بصري وجزء الكتروني بصري يحتوي على كاشف ضوئي رباعي. والجزء الميكانيكي المكون من اسطوانة من الالمونيوم بأبعاد هندسية محددة وملحقاتها والأبعاد البورية للمرايا المستخدمة في التوصل للمدى المطلوب للتتبع.

1. Introduction

The basic purpose of the optical parts in the tracking system is to collect the radiation flux and deliver it to the detector. Any optical system consists of one or more reflective or refractive elements. All these elements are considered to be centered; that is, the center of curvature lies on the line called the optical axis. There are many reflective systems; Newtonian mode suggests that the flat secondary mirror may be placed so as to bring the focus to the side of the telescope. This is a convenient location for the detector since it minimizes blockage of the incoming rays. The cassegranian system uses a convex secondary mirror placed inside the prime focus; it redirects the ray through the hole in the primary mirror to a new focus.

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2. The hardware part

2.1 The optical receiver unit

The optical receiver consists of two reflective elements; these elements are arranged as a cassegranian mode and have been coated by reflective material. The first element is a concave (primary) mirror with a 60 mm in focal length and 100 mm in diameter and lies in the direction of incoming rays that scattered from the target. The second element is a plane mirror. The diameter of this mirror is 50 mm. The position of the primary and secondary mirrors must be accurately maintained in relation to one another. This relation will be demonstrated laterally as shown in fig. (1).

Figure (1): The Designed Optical Unit

2.2 The optoelectronic unit

Description of quadratic detector

The photo detector focal plane is divided into four equal parts. All four detector quadrants are summed together for the sum channel processing, the top two quadrants are summed together (top half) and the bottom two quadrants are summed together (bottom half) for elevation angle estimation. Similarly the left and right detector halves are used for azimuth angle estimation. In this fashion, the elevation and azimuth dimensions can be treated independently.

The photo detector receives the incident light and converts it into a response that can be measured. This response or output is electric. It gives a

measure of the intensity of the incident light. To utilize the information related to the position of the target, a method must be applied to convert the laser signal that reflected from the target to electrical signal. A silicon quadrant photodiode detector (QD 7-5 652-027) is used in this work as a sensor of tracking system. The detector receives the radiation signal that is directed toward it and converts this signal to four electrical signals. This detector is located at a hole, which is located in the center of the primary mirror. The diameter of this hole is the same or larger than that of the detector. The active area of this detector is 7mm^2 with 3mm in diameter. Figure (2) shows the detector configuration with the four distinct active areas (anodes). The cathode is common for all four regions (anodes).

Figure (2) Detector's Configuration
3-2-2-2 The detector parameters

There are several quantities are often used to describe the characteristics of a detector, which are: the responsivity, the noise, noise equivalent power, the detectivity, normalized detectivity, the time constant, and the quantum efficiency. In order to determine the detector efficiency, their parameters must be measured and calculated, as following:

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3.1 Responsivity:

The responsivity is defined as the detector output per unit of input power. The units of responsivity are ampere /W or V / W, depending on whether the output is an electric current or a voltage. The responsivity varies with wavelength. Using (DSR optronic system) performs the detector spectral response measurement. This system contains Tungsten-Halogen light source of 200 Watt as power. The dynamic range of this source is (200-1400) nm using special power supply, and monochromator that provides a ray of light with wavelengths ranging between (200-1200) nm and using a grating having resolution power of 10nm. The change in the light power with the variation of the wavelengths was measured, and the output current for each detector's element as a function of wavelength was also measured. Finally, the responsivity as a function of wavelength in (Amp/Watt) was calculated. [1]

Noise is another parameter, which refers to the random fluctuation that interferes with all detectors' electrical signals. It may arise in the detector itself, in the incident radiant power to which detector responds, and in the electronic system following the detector. [2]

There are two primary kinds of noise. First, is the shot noise (I_{sh}) current from each quadrant due to dark current, and can be described as:

$$I_{sh} = \sqrt{2 \times q \times I_d \times \Delta f} \quad (1)$$

Where q is the electron charge, I_d is the dark current; Δf is the detector electrical bandwidth which is equal to 1 Hz. The second noise is the thermal noise which is given by: [3]

$$I_{th} = \sqrt{\frac{4 \times k \times T \times \Delta f}{R_L}} \quad (2)$$

where R_L is the load resistance, k is Boltzman's constant, and T is the absolute temperature of R_L .

The theoretical noise current described at the detector output, is:

$$I_N = \sqrt{(I_{sh})^2 + (I_{th})^2} \quad (3)$$

The noise equivalent power (NEP) is defined as the radiant power that produces a signal voltage or (current) equal to noise voltage or (current) of the detector. This parameter is calculated during the work by using the relation: [3]

$$NEP = \frac{I_N}{R_\lambda} \left[\frac{Watt}{\sqrt{Hz}} \right] \quad (4)$$

Another quantity, that is, the detectivity (D), or the reciprocal of NEP, therefore, it can be calculated as:

$$D = \frac{1}{NEP} \quad (5)$$

$$D^* = D \sqrt{A \times \Delta f}$$

Since many detectors have (NEP) proportional to the square root of their area, D^* is dependent on the area of the detector and provides a measure of the intrinsic quality of the detector material itself, independent of the area with which the detector happens to be made. D^* it is one of the terms that often used to describe the optical and infrared detectors. This parameter represents the detectivity refer to an electrical bandwidth of 1Hz and detector area of 1 cm² and is given by:[3]

$$D^* = D(A_d \Delta f)^{1/2} = \frac{(A_d \Delta f)^{1/2}}{NEP}, \frac{Cm.Hz^{\frac{1}{2}}}{W} \quad (6)$$

The frequency response of a detector is the variation of responsivity

or radiant sensitivity as a function of the modulation frequency of the incident radiation. Time constant can be defined as the time that takes for the detector's output to reach 63 % of its final value after a sudden change in the irradiance. Theoretically, it can be calculated by using the following relationship:[3]

$$T_{const} = R_L \times C_J \quad (7)$$

where : C_J is the junction capacitance. This capacitance can be measured by using RLC impedance analyzer device. The speed of response (rise time) is calculated by:

$$t_r = 2.2 \times R_L \times C_J \quad (8)$$

The quantum efficiency (η) is basically another way of expressing the effectiveness of the incident radiant energy for producing electrical current in a circuit. And it can be defined as the number of carriers generated per incident photon and it is calculated from the following equation: [2]

$$\eta = R_\lambda \frac{hc}{q \times \lambda_{max}} \quad (9)$$

where: (η) is the detector quantum efficiency, (q) is electronic charge, (c) is the speed of light, (h) is Planck's constant, and (R_λ) is detector's responsivity in Amp/Watt. The quantum efficiency is a percentage value.

3.2 Measurements of the field of view (FOV) of the Detection's unit.

Since the quadrant detector represents the most important elements for this tracking system, it is important to determine the field within which the detector can be viewed (FOV). Two methods have been used to determine FOV, the first is by fixing the receiving unit on a circular stage divided into 360° and aligned with the center of the light source where a Helium-Neon laser has been used. The angle between the optical axis of the receiving unit and that for the laser source is equal to zero. This means that the spot lies at the center of the detector as shown in figure (3). In this case,

a maximum output voltage is provided and monitored by digital voltmeter connected to the quadrant detector. After that, the receiving unit is rotated with steps of 5 degrees to the left side toward the decreasing of the output voltage until the voltmeter record zero volts. Then, this process is to be repeated to the right side.

Figure (3): Measurement of the field of view

The result of the left and right rotating process is a gaussian curve for the output voltage as a function of angle of rotation, where the maximum of this curve is at zero degree. The degrees at Full width of Half Maximum (FWHM) represent the field of view.[4]

The second method that is used to determine FOV is by utilizing the following equation:[4]

$$F.O.V = \frac{D_d}{F}, \text{ where } D_d \text{ is the diameter of the detector, } F \text{ is the focal length}$$

for the concave mirror .This is a general form ,but in this work, the following formula was used:

$$F.O.V = \frac{D_d}{F - X} \quad (10)$$

X is the distance between the detector and the focus.

4. The Mechanical Unit

It is a mechanical cavity constructed from aluminum cylinder. The primary and secondary mirrors, as well as the detector, must be accurately

maintained in precise position to one another. This is generally done by constructing a mechanical cavity with which both mirrors are supported. The primary mirror is usually mounted directly in one end of this cavity, while the other (plane mirror) mounted at the other end which is covered by a transparent material (glass) in order to permit the laser beam to pass through it. Figure (4) shows an external view for the mechanical unit, whereas Figure (5) shows a cross section of this unit.

Because it is difficult to find a hollow cylinder of aluminum, an aluminum rod 30-cm in length and 18 –cm in diameter has been casted in a foundry and formed by a lathe machine to get 20-cm in length and 11 –cm in inner diameter. Fine threads with 1.25-mm pitch of 10-cm length are made on the cylindrical tube for fine axial adjustment of the concave mirror. A cover of aluminum is formed to adjust the movement of the plane mirror towards the concave mirror. Aluminum has been chosen because it is not heavy and can resist the corrosion.

The internal length of this cavity represents the distance between the two mirrors and can be determined as following:

Figure (4): The external view for the mechanical unit

In order to determine the detector and secondary mirror position relative to the primary mirror, let us consider for a start that the secondary mirror does not exist, and the detector is in the position (a), Figure (6). From the following relation, we get:

$$\frac{Y}{F - g} = \frac{r_{opt.}}{X} \quad (11)$$

where Y is the radius of the primary mirror, F is the focal length, r_{opt} represents the radius of tracking region, and X is the distance between the detector and the focal point

then:

$X = \frac{r_{opt} \times (F - g)}{Y}$ represents the detector position relative to the focus

$X' = F - X$ represents the residual distance from the focal length.

Now, we shall place the secondary mirror in the middle of the distance X , then $X/2$ represent the position of the secondary mirror relative to the primary mirror. The final step is to place the detector in the new position, which is the position b.

Figure (6): The mechanical head layout

5. Results and Discussion

The quadrant detector parameters calculations

The quadrant detector parameters, measurement and calculation are presented grouping together with these parameters, which are taken for the detection unit for AS-30L missile as shown in Table (1).

The Spectral Response

The spectral response of the detector used is shown in Figure (7). Its peak response is in the near infrared region (NIR) of the electromagnetic spectrum, which is 0.5 Amp. / Watt at $\lambda=950\text{nm}$.

Table (1): Value of the parameters for AS_30L and the designed system.

	AS-30L	The Designed System
Active area(mm ²)	314	7
Spectral response(nm)	400-1200	400-1100
Peak spectral response A/W	0.54	0.5
C _J (PF)	170	80
I _d (nAmp.)	1	3
Rise time (nsec)	18.7	15
I _n (nAmp.)	1.788×10^{-14}	1.2×10^{-11}
NEP (watt)	3.31×10^{-14}	2.57×10^{-11}
D (watt ⁻¹)	3.015×10^{13}	0.389×10^{11}
D* (cm.Hz ^{0.5} /watt)	5.34×10^{13}	0.1×10^{11}
FOV _{all} (Degree)	22.9	2.87
FOV _{trav} (Degree)	8.1	2.02
Quantum efficiency	60.8%	65%

Figure (7) The spectral response of the quadrant detector.

Measurement of the Noise Current

We recall that the noise current consists of two components:
Shot noise that is given by:

$$I_{sh} = \sqrt{2 \times q \times I_d \times \Delta f}$$

$$I_d = 3 \times 10^{-9} \text{ Amp.}$$

$$\therefore I_{sh} = 3.09 \times 10^{-14} \text{ Amp.}$$

and the *thermal noise* which is given by:

$$I_{th} = \sqrt{\frac{4 \times k \times T \times \Delta f}{R_L}}$$

$$I_{th} = \sqrt{\frac{4 \times 1.38 \times 10^{-23} \times 300 \times 1}{100}}$$

$$I_{th..} = 1.28 \times 10^{-11} \text{ Amp.}$$

The total noise current is given by:

$$I_{tot.} = \sqrt{(I_{sh})^2 + (I_{th.})^2}$$

$$I_{tot.} = 1.2 \times 10^{-11} \text{ Amp}$$

These values are the same for all the quarters of the quadratic photodiode detector.

NEP, D, D?'s Calculation:

As shown previously, all these parameters are related to one another, and can be calculated from the following equations:

$$NEP = \frac{I_{tot.}}{R_{\lambda}} = \frac{1.2 \times 10^{-11}}{0.5} = 2.57 \times 10^{-11} \text{ W}$$

The detectivity D, and specific detectivity, D^{*}, were calculated as below:

$$D = \frac{1}{NEP} = 0.389 \times 10^{11} \text{ W}^{-1}$$

$$D^* = \sqrt{A \times \Delta f} \times D$$

$$D^* = 0.1 \times 10^{11}, \frac{\text{cm.Hz}}{\text{W}}$$

Measurement of the field of view

The field of view can be calculated by using (eq. 10) and it is found to be:

$$F.O.V = \frac{D_d}{F - x}$$

where D_d represents the detector's diameter.

$$F.O.V = \frac{3mm}{60mm} = 2.87^\circ$$

As it is mentioned in chapter two, the photosensitive area of the detector does not represent the tracking region. Accordingly, the FOV that is measured and calculated represents the detection's field of view. Therefore the F.O.V. that relates to the tracking mode can be determined as following;

$$F.O.V_{track} = \frac{D'_d}{F - X} \quad (12)$$

where D' represents the diameter of the tracking region and equal to:

$$2 \times r_{opt.}$$

$$\therefore r_{opt.} = \frac{1.5mm}{\sqrt{8}}$$

$$r_{opt.} = 1.06mm$$

$$\therefore F.O.V_{track} = \frac{2.12}{60} = 2.02^\circ$$

If the return beam is larger than the receiver F.O.V., all the laser energy outside the receiver FOV will be lost, that is why the optics was used. If the returned laser beam is smaller than the receiver FOV, the noise will be large [4]

6. The Quantum efficiency

The quantum efficiency is a function of the spectral response so that the maximum quantum efficiency is at the wavelength ($\lambda_{\max.} = 950\text{nm}$). In quadrant detectors, the separations between the segments have an effect on the total quantum efficiency by an amount that depends on the size of this separation.[5] The quantum efficiency at $\lambda_{\max}$ of the detector is found by using the following equation:

$$\eta = R_{\lambda} \frac{hc}{\lambda_{\max} q}$$

$$\eta = \frac{1.24 \times 10^{-4} \times R_{\max.}}{\lambda_{\max.}}$$

$$\therefore R_{\max.} = 0.5 \text{ Amp./Watt.}$$

$$\therefore \eta = \frac{1.24 \times 10^{-4} \times 0.5}{0.95 \mu\text{m}} \times \frac{100}{100}$$

$$\eta = 65 \%$$

Calculation of the atmospheric transmission

The laser beam is attenuated through the atmosphere. The transmittance of the laser beam through the atmosphere is calculated for a given wavelength, initial power, and visual range for (1-10) Km as ranges.

Presentation of laser beam's behavior

In the present model, P_0 is the initial power that is transmitted from the laser sources. This power will be attenuated in passing through the atmosphere. The laser beam has a divergence,[6] therefore, the spot of laser that falls on the target, reflected from the target, and then received by the receiving unit, has a different areas depending on the range [7, 8,3]. The laser beam that reaches to the target is scattered in all directions, therefore it will be assumed that 10% of the power that reaches the target (P_1) represents (P_2), which is directed back toward the receiving unit that is in the same direction of the transmitting unit.

It is taken into account in calculating the power that is received by the detection unit, i.e., P_3 , that the value of this power must be larger than the minimum detectable power for the detection unit.

From Figure (8), A_1 represents the area of target and A_2 represents the area of the laser spot at the target zone which is equal to:

$$A_2 = \pi(r_2)^2 \quad (13)$$

This equation represents the area of the laser spot at the target region, r_2 denotes the radius of this area and equals to:

$$r_2 = R \times \tan \frac{\beta}{2} \quad (14)$$

where β is the beam divergence.

Figure (8): Divergence of the laser beam with the range.

$$A_3 = \pi (r_3)^2 \quad (15)$$

is the laser spot's area at the receiving region where r_3 is the radius of A_3 and equal to:

$$r_3 = R' \times \tan \frac{\beta}{2} \quad (16)$$

The power reaching the target's position (P_1) can be represented as:

$$P_1 = \frac{P_o \times A_1 \times \tau}{A_2} \quad (17)$$

Considering then percent (10%) from the upper value will be returned directly toward the target to form P_2 , then:

$$P_2 = 0.1 \times P_1 \quad (18)$$

The power that received by the receiving unit is:

$$P_3 = \frac{P_2 \times \tau \times A_c}{A_3} \quad (19)$$

where A_c denotes the area of the concave mirror.

This model is supported by using the Visual Basic program to determine the behavior of P_3 as a function of the range. Figure (9) represents the main menu of the program.

The screenshot shows a Visual Basic window titled 'Form2'. It has a section titled 'Input The Fowlling Data' with the following labels and values in text boxes:

- Initial Power (W) = 3.3e6
- Wavelength (um) = 1.06
- Transmittance = .96
- Visibility (km) = 8
- Target Area (m^2) = 1
- Min. Real Range (km) = 1
- Max. Real Range (km) = 10
- Real Range Step (km) = .1

Below this section is an 'Action' section with three buttons: 'Calculate', 'Plot', and 'Exit'.

Figure (9) The main menu of the program

7. Conclusions

1. The pulsed laser used here has a good diverging in both azimuth and elevation directions to detect the target at any point.
2. The Field of view of the tracking zone of the quadrant detector is less than that for the all surface for the detector.
3. The theoretical transmission model can be used as a reference model to determine the behavior of any laser beam.
4. In this system for compactness the optical design mode is the cassagranion one.
5. Experimental results have proven that a very fine tracking has been observed between the source and the target.
6. Based on the results shown, a precision tracking algorithm may be adopted which is capable of estimating the target centroid with very good pixel accuracy.
7. The resolution of the tracking system is 0.112 degree/pixels.

8. References

- [1] Christopher C. Davis, Laser and Electro Optics, Fundamentals and Engineering, 1996.
- [2] S.S.Amed, Automatic Real-TimeVideoTrackinSystem, 2002.
- [3] R. D. Hudson, J. Wiley, and Sons, Infrared system engineering, new York, 1969.
- [4] F. A. Jenkins, H. E. White, Fundamental of optics, 1985.
- [5] R. A. Smith, Jones, and R. P. Chsmar, Detection and measurement of infrared radiation, 1968.
- [6] G. Marola, D. Santerini, and G. Prati,, Stability Analysis of Direct Detection Cooperative Optical Beam Tracking, IEEE Transaction on Aerospace and electronic system, Vol. 25, No. 3,1989.
- [7] Zarko, Barbaric, Infrared homing guidance systems, Belgrade, 2001.
- [8] F. X. Kneizys, S. A. Clough, and E. P. Shettle, Atmospheric attenuation of laser radiation, SPIE laser beam propagation in the atmosphere, Vol. 410, 1983.