Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 2026, Iss. 103, pp. 36–40

UDC 621.396.96

Optimization of Laser Hazard Warning Systems

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Actuality. Active and semi-active optical guidance systems for projectiles and missiles at a target mainly use a laser beam from a Laser danger Warning System (LWS) designed for prompt notification of the fall of a laser targeting beam on an important protected object. Photodetectors are used to register the laser beam hitting the surface of the protected object. To reduce the likelihood of a false alarm, it is necessary to achieve the possibility of receiving the largest possible optical signal on photodetectors. **Setting the task**. To increase the accuracy of the generated alarm signal based on the signals of photodetectors detecting direct laser beam hits, it is proposed to install additional remote photodetectors for recording reflected and diffusely reflected optical signals. **Method**. The problem of optimal selection of the ratios of distances from the laser to the target and from the target to additional receivers in LWS with remote photodetectors has been formulated and solved. Two subtasks are formulated: in the first, the target indicated by the laser belongs to the enemy, and in the second, the opposite side. It is shown that when optimizing systems of laser-guided missiles and projectiles, taking into account the LWS introduced by the enemy, it is possible to use the theory of the Laser Detection and Ranging (LADAR) systems. **The result** is that the application of the theory of radar systems has made it possible to optimize the functioning of the attacking side in terms of optimal choice of the distance to the enemy using the LWS with remote photo sensors.

Keywords: LADAR; photodetector; optimization; laser; laserbeam

DOI: 10.64915/RADAP.2026.103.36-40

1 Introduction

Laser danger Warning Systems (LWS – Laser Warning Systems) are designed to protect personnel and important military installations from laser-guided missiles, shells or bullets from enemy snipers. The basic principle of operation of laser warning systems is described in detail in many works. Thus, a new design of LWS was proposed in [1], containing a spatially modulated Michelson interferometer and a fiber optic antenna. The interferometer distinguishes laser radiation from background radiation. Using the Fourier transform, information about the spectrum of laser radiation is obtained. In [2], it is reported about the creation of an angle of incidence sensor using mirrors. It is noted that the proposed design provides a viewing angle of up to 120°. The paper [3] reports on the construction of LWS using a line of discrete photodiodes. It is noted that the proposed design ensures high accuracy in determining the beam angle. The possibilities of using a neuromorphic camera to provide a hemispherical viewing angle are considered in [4]. It is noted that the accuracy of recording the angle of entry at the level of 0.05 degrees in the visible region of the spectrum has been achieved. In [5], it is reported about the creation of an on-board LWS having a wide range of wavelengths with the ability to detect a code message contained in a pulsed sequence of laser radiation. It is noted that the LWS should take into account the possibility of changing the distance between the emitter and the system itself and be protected from interference. As noted in [6], the photodetectors used in LWS should cover a wide range of wavelengths from 500 nm to 1700 nm, and be capable of detecting enemy code. According to [7], an LWS with an optical system has been created that provides a signal-to-noise ratio of at least 160 db and is capable of detecting laser beams from a distance above 15 km at a low temperature. As reported in [8], the use of photodetectors based on nanostructures can significantly improve the basic characteristics of LWS. In [9], it is noted that it is necessary to take into account the attenuation of the laser beam in the atmosphere when organizing measures to counteract the target-pointing beam. It is noted in [10] that reducing the beam diameter using newly developed optics to 350 microns made it possible to achieve a signal-to-noise ratio of 175 dB, which in turn reduced the number of “false alarms”.

At the same time, it should be pointed out that it is possible to increase the sensitivity of such systems, which consists in the fact that the laser beam passing through kilometers distances increases in diameter to several tens of centimeters. However, the optical node of the warning system receives only a part of the energy of the beam. In this case, the rest of the energy of the laser beam is lost. If we use the remote photodetectors with a large area of the sensitive input part and set them at a certain distance from the object to receive all the scattered and reflected radiation from the object, as shown in Fig. 1b, then it would be possible to register the incident laser beams more effectively.

It should also be noted that the fixation of the laser beam on the surface of the protected object can be carried out in two ways:

1. By placing highly sensitive photodetectors on the surface of the protected object to detect the laser beam hitting the surface of the object (Fig. 1a);

2. By placing remote photodetectors in front of the protected objects to register laser beams reflected from the surface of the protected object (Fig. 1b).

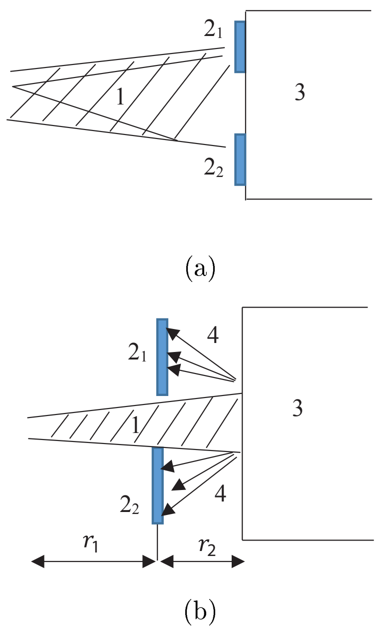

Fig. 1. Block diagram of laser hazard warning systems: (a) a variant of the system where the photo sensors are installed on the surface of the object; (b) a variant of the system with remote photo sensors. The numbers indicate: 1 – laser beam; 2_1, 2_2 – photo sensors; 3 – protected object; 4 – reflection of laser beams

The following dual problem is considered in this article:

- Task 1-1 is to find the optimal ratio of r_1 and r_2 (see Fig. 1b) if the object belongs to the enemy, and the laser belongs to the forces advancing on the enemy;

- Task 1-2 is to find the optimal ratio of distances r_1 and r_2 (Fig. 1b) if the laser belongs to the enemy and the object belongs to the side defending against the enemy.

It should be noted that with regard to the principle of operation of the LWS (the propagation of a laser beam and its reflection from an object), the LWS is completely similar to the principle of Laser Detection and Ranging (LADAR) operation and the LADAR analysis method can be applied. As demonstrated in [5,12,13] LADAR is a laser radar designed to determine and study the shape and configuration of objects at a certain distance. To solve the tasks set above, we will use the well-known expressions obtained during the analysis of the LADARs.

As shown in [14], the power equation of the reflected laser beam in LADAR can be written as follows:

$$P_r = \frac{4KP_5T_{A_1}\eta_t}{\pi\cdot\varphi^2 r_1^2}\cdot\Gamma\cdot\frac{T_{A_2}}{\pi\cdot r_2^2}\cdot\frac{\pi D^2\eta_r}{4}, \quad (1)$$

where
P_r – the power of the received reflected signal,
P_5 – the power of the laser source used;
K – a function that characterizes the profile of the laser beam;
T_{A_1} – transmission of the atmosphere in the direction from the source to the target;
η_t – optical efficiency of the transmitter;
φ – the beam thickness in radians r_1 is the distance from the transmitter to the target;
Γ – the cross-section of the laser beam on the target surface and in m^2;
T_{A_2} – transmission of the atmosphere from the target to the receiver;
r_2 – the distance from the target to the receiver;
D – the diameter of the receiver aperture in meters;
η_r – optical efficiency of the receiver.

Thus, expression (1) allows us to calculate the power of a laser radar as a product of four multipliers:

1. Propagation of the laser beam to the target.

2. Reflection of the beam from the target.

3. The movement of the scattered (reflected) beam towards the receiver.

4. Collecting the scattered light to the receivers.

As can be seen from expression (1), it is symmetrical and, in general, the complete block diagram of the LWS can be represented similarly to the diagram shown in Fig. 2.

The *purpose of this article* is to find the optimal ratio between r_1 and r_2 at which the reflected signal power can reach extreme values. At the same time, if the extremum is the minimum, then this can be considered the best option for the attacking side. Otherwise, if the extremum is the maximum, then this option is optimal for the defending side.

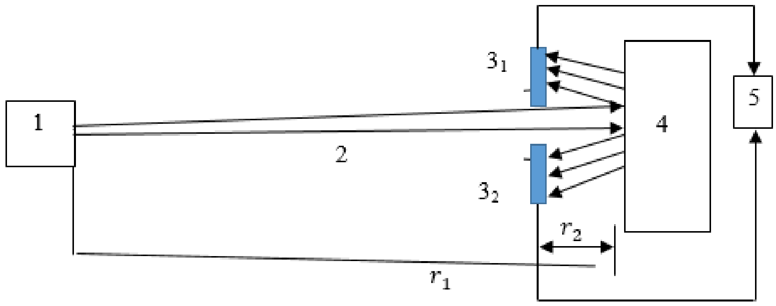

Fig. 2. Block diagram of the LWS. The numbers are indicated: 1 – laser guidance source of the attacking side; 2 – laser beam; $3_1, 3_2$ – photodetectors; 4 – protected object; 5 – control device

2 Materials and methods

As can be seen from expression (1), it is symmetric with respect to r_1 and r_2; therefore, any optimal ratio obtained is in the form:

$$r_1 = f(r_2), \tag{2}$$

also becomes optimal about the form:

$$r_2 = f(r_1). \tag{3}$$

Let's represent expression (1) in the following form:

$$P_r = \frac{C_1}{r_1^2 \cdot r_2^2}, \tag{4}$$

where

$$C_1 = \frac{4KP_5T_{A_1}\eta_t}{\pi \cdot \varphi^2} \cdot \Gamma \cdot \frac{T_{A_2}}{4\pi} \cdot \frac{\pi D^2 \eta_r}{4}, \tag{5}$$

where $C_1 = const.$

Next, we introduce following function for consideration:

$$r_1 = f(r_2). \tag{6}$$

Taking into account expression (6), expression (4) has the form:

$$P_1 = \frac{C_1}{r_2^2 \cdot f^2(r_2)}. \tag{7}$$

In principle, the following ordered set can exist, where all neighbor elements of the set differ each from the other by a constant positive value of increment:

$$R_2 = \{r_{2i}\}; \quad i = \overline{1,n}, \tag{8}$$

where the nearby elements of the set differ by an amount $\Delta r_2 = const$, i.e., in practice, it can take on a large set of discrete quantities. Obviously, if $n \to \infty$ the following target functional F can be constructed based on expression (7):

$$F = \int_0^{r_{2\max}} \frac{C_1}{r_2^2 \, f^2(r_2)} dr_2. \tag{9}$$

According to the method of unconditional variational optimization, to calculate the optimal type of function, we should impose some restrictive condition on this function in the form:

$$\int_0^{r_{2\max}} f(r_2) dr_2 = C_2; \quad C_2 = const. \tag{10}$$

Taking into account expressions (9) and (10), we formulate the following optimization target functional:

$$F_1 = \int_0^{r_{2\max}} \frac{C_1}{r_2^2 \cdot f^2(r_2)} dr_2 + \lambda \left[\int_0^{r_{2\max}} f(r_2)\, dr_2 - C_2 \right], \tag{11}$$

where λ is the Lagrange multiplier.

The solution of optimization problem (11) according to the Euler method must satisfy the condition [10]:

$$\frac{d\left\{\frac{C_1}{r_2^2 \cdot f^2(r_2)} + \lambda f(r_2)\right\}}{df(r_2)} = 0. \tag{12}$$

From expression (12) we can find:

$$-\frac{2C_1}{r_2^2 \cdot f^3(r_2)} + \lambda_1 = 0. \tag{13}$$

From expression (13) we can obtain:

$$f(r_2) = \sqrt[3]{\frac{2C_1}{\lambda_1 \cdot r_2^2}}. \tag{14}$$

According to the Lagrange criterion, solution (14) leads the functional (11) to a minimum value if the second derivative of the under integral expression in (11) with respect to the searched function is always a positive quantity.

3 Discussion

Thus, the problem optimal choice of the ratio of distances from the laser to the target and from the target to the proposed additional receivers in LWS as remote photodetectors has been formulated and solved. Two subtasks are considered: in the first case, the pointing laser belongs to the enemy, and in the second to the opposite side. In the context of solving the first subtask, a condition has been obtained, under which the signal generated in the remote photodetectors reaches a minimum, which is undesirable for the defending side. In the context of the second subtask being solved, a condition has been obtained under which a minimum signal is generated on the external photo sensors of the defending enemy, which can be considered the optimal mode for the forces advancing on the enemy.

To evaluate the effectiveness of the proposed method of building an alert system, a simplified efficiency calculation is performed. Let's assume that the power of the laser beam incident on the surface of the object is I. Due to the scattering of the beam, an optical signal with a power of I is converted into an electrical signal.

$$I_1 = I - \Delta I,$$

where ΔI is the optical signal power used for scattering.

On the other hand, due to the introduced innovation, power will be converted into an electrical signal.

$$I_2 = I - \Delta I + \Delta I_1,$$

where ΔI_1 is the part of the power ΔI that can be converted into an electrical signal due to the introduced innovation. The winning ratio is defined as

$$k = \frac{I_2}{I_1} = 1 + \frac{\Delta I_1}{I - \Delta I} = 1 + \frac{1}{\frac{I}{\Delta I_1} - \frac{\Delta I}{\Delta I_1}}.$$

Thus, even if

$$\frac{I}{\Delta I_1} = 10; \quad \frac{\Delta I}{\Delta I_1} = 2,$$

we get $k = 1 + 1/8$, i.e. we get a win of $k = 1,125$ or 12.5% of the win.

Conclusion

It is shown that when optimizing systems of laser-guided missiles and projectiles, taking into account the use of LWS by the enemy, it is possible to use the theory of the LADAR systems for additionally installed photodetectors. The application of the theory of the LADAR systems made it possible to optimize the functioning of the attacking side in terms of the optimal choice of the distance to the enemy using the LWS with remote photo sensors.

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Оптимізація систем попередження про лазерну небезпеку

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Актуальність. Активні та напівактивні оптичні системи наведення снарядів та ракет на ціль переважно використовують лазерний промінь системи лазерного попередження про небезпеку (LWS — Laser Warning Systems). Охоронні системи, для реєстрації потрапляння лазерного променя на поверхню об'єкта, що охороняється, використовуються фотодетектори. Щоб зменшити ймовірність хибної тривоги, необхідно досягти умов отримання максимально можливого оптичного сигналу на фотодетекторах.

Постановка завдання. Для підвищення достовірності генерованого сигналу тривоги на основі сигналів фотодетекторів, що виявляють прямі потрапляння лазерного променя, пропонується встановити додаткові виносні фотодетектори для реєстрації відбитих та дифузно відбитих оптичних сигналів.

Метод. Сформульовано та вирішено задачу оптимального вибору співвідношень відстаней від лазера до цілі та від цілі до додаткових приймачів у системах лазерного наведення з дистанційними фотоприймачами. Сформульовано дві підзадачі: у першій, ціль, що вказується лазером, належить противнику, а у другій – протилежній стороні. Показано, що при оптимізації систем лазерно-наведених ракет та снарядів можна використовувати теорію систем лазерного виявлення та визначення дальності (LADAR — Laser Detection and Ranging).

Застосування теорії радіолокаційних систем дозволило оптимізувати функціонування атакуючої сторони з точки зору оптимального вибору відстані до противника за допомогою системи LWS з дистанційними фотодатчиками.

Ключові слова: LADAR; фотодетектор; оптимізація; лазер; лазерний промінь