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SYSTEM FOR RECOGNITION OF OPTICAL TOOLS, BASED ON FRACTAL MATHEMATIC VIEWS

Система для виявлення оптичних приладів, заснована на уявленнях фрактальної математики

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The aim of the paper is development of laser optoelectronic system for recognition of optical tools. The main algorithm of the system is based on fractal insights about the structure of the optical signal and determination of the fractal dimension intensity distribution in a cross-sectional plane of the laser pulse reflected from the optical target. The authors analyze the application of topological methods and tools for researching of complex physical processes, in particular the process of optical signals propagation in an inhomogeneous atmosphere. It is proved that the Lyapunov indexes, Kolmogorov-Sinai and Shannon entropies, as well as the fractal dimension can be used to succesfull study of the complex optical signals. The authors propose an approach for identification of optical objects that based on fractal analysis of the signals reflected from objects' surfaces. It is proved that the approximation of fractal dimension value of the signal to 1 is a condition for identification of optical devices. Because of the atmospheric scattering of laser pulses and noise exposure, this value may be in the range between 1.1 and 1.3. To classify the type of optical device (binoculars, video camera, etc.) along with the fractal dimension, a group of other fractal characteristics (the type of fractal signatures, the type of spatial spectrum and spatial frequency values), that characterize the signal structure, should be used also. The developed fractal model is proposed to use in the infrared system for searching of hidden optical surveillance devices. The authors propose the principles of operation, common structure and calculation results for optical part of the system. It is proved that the use of the fractal model in the algorithm of information processing will allow the system as to search and determine coordinates of target so to classify objects and determine erroneous targets too.

Метою статті є створення лазерної оптоелектронної системи виявлення та розпізнавання оптичних систем. Головний алгоритм системи базується на фрактальних уявленнях щодо структури оптичного сигналу та визначенні фрактальної розмірності розподілу інтенсивності лазерного імпульсу, відбитого від об›єкта розпізнавання, в площині його поперечного розрізу. Авторами виконано аналіз застосування методів та інструментів топології для дослідження складних фізичних процесів, зокрема, процесу розповсюдження оптичних сигналів у неоднорідній атмосфері. Доведено, що показники Ляпунова, ентропії Колмогорова-Сіная та Шеннона, а також фрактальна розмірність можуть бути застосовані для дослідження оптичних сигналів. Запропоновано підхід до ідентифікації оптичних об'єктів, заснований на фрактальному аналізі відбитих від них сигналів. Доведено, що наближення значення фрактальної розмірності сигналу до одиниці є умовою для ідентифікації оптичних пристроїв. Унаслідок атмосферного розсіювання та впливу шумів ця величина може міститися в інтервалі між 1.1 та 1.3. Для класифікації типу оптичного пристрою (бінокля, відеокамери або ін.), разом із фрактальною розмірністю, повинна бути застосована також група фрактальних характеристик, що складається з типу фрактальних сигнатур, типу просторового спектра та значень просторової частоти, які характеризують структуру сигналу. Розроблену фрактальну модель запропоновано для використання в інфрачервоній області спектра випромінювання системи пошуку прихованих оптичних пристроїв спостереження. Авторами наведено принципи роботи, структуру та виконано розрахунки оптичної частини системи. Доведено, що використання розробленої фрактальної моделі в алгоритмі опрацювання інформації системи дозволить їй не лише здійснювати пошук та визначати координати, а й класифікувати об'єкти та визначати помилкові цілі.

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Ключові слова: *оптична система, оптичний сигнал, інтерференція, фрактальна розмірність, лазер.*

INTRODUCTION

A wide range of cybersecurity tasks that maintain commercially sensitive information covers the tasks of protection against unauthorized video and photo recording. Its implementation is performed by laser optoelectronic systems (LOS), allowing to locate the hidden optical devices (OD), such as binoculars, video and photo cameras.

The principle of LOS operation is based on the process of scanning the space by a laser beam and the task of determining the location of the reflective surface, which is the objective lens. More sophisticated LOS allows not only to determine the coordinates of the hidden optical surveillance devices, but also to recognize and classify them. If the physics of OD coordinates determination is described in detail in the literature that deals with optical location [1—2], then the issue of recognition and classification is a business secret of the manufacturer.

The classification of OD is related to object recognition tasks. The object recognition includes three stages: obtaining information on the object; selection and evaluation of natural and artificial features (the simplest characteristics or properties); recognition and classification of an object on the basis of the analysis of the selected features. The most popular methods are: Fourier analysis and correlation analysis, contour analysis, fractal analysis, wavelet analysis, search method and others [3].

The mentioned fractal analysis relates to topological methods used to analyze time-series processes and images, including the objects classification during radiolocation [4]. The aim of the paper is development of the laser optoelectronic system for recognition of optical tools, based on fractal mathematic view.

THEORETICAL STUDIES OF THE LOS MAIN PARTS

Let's consider an optical system that perceives radiation from a surface lighted by a laser, the principal scheme of which is shown in Fig. 1.

The laser with the 2ω difference angle lights a surface that is at a distance p from the optical system. We can assume that the solid angle Ω is equal to [5]:

$$\Omega = \pi \cdot \omega^2. \quad (1)$$

The emission in the Ω bodily angle is uniform. Then the emission intensity in the direction of the laser axis is equal to:

$$I_e = \Phi_e / \pi \cdot \omega^2, \quad (2)$$

where Φ_e is the laser radiation flux.

With normal falling of rays on the lighted surface, E_e light intensity is equal to:

$$E_e = \tau_a \cdot I_e / p^2, \quad (3)$$

where τ_a is the atmosphere transmittance.

Assuming that the lighted surface is a Lambert surface with ρ reflection coefficient, we find the surface radiance:

$$L_t = \rho \cdot E_e / \pi. \quad (4)$$

The diameter of the surface lighted with laser is:

$$D_0 = 2\omega p. \quad (5)$$

An increase in the optical system at considerable p distance can be assumed to be equal to:

$$B = f' / p. \quad (6)$$

Image diameter in sensory element:

$$D_0' = D_0 \cdot \beta. \quad (7)$$

Since the laser system should operate at a distance of up to 3000 m (at larger distances it is not necessary), and the focal length of the gluing lens (collimator of the receiving optics) is 150 mm (existing lenses in the market), the diameter of the spot radiation in the focus of the lens is 200 μm.

If the image fits into the photosensitive surface of the sensory element, then the required relative diameter of the receiving optical system will be as follows:

$$D / f = 2\sqrt{i_{\min} / \tau_a \cdot \tau_{lf} \cdot \tau_{os} \cdot Q_0' \cdot S(\lambda) \cdot L_e}, \quad (8)$$

where τ_a, τ_{lf}, τ_{os} are atmospheric transmittance coefficients, light filters, optical system; Q_0' — object image area; $S(\lambda)$ — absolute spectral sensitivity of the sensory element to monochromatic laser emission.

The area of the photosensitive element is 200 μm, therefore, based on the research paper [6], the diameter of the recording optical system is 48 mm, and, taking into account all tolerances, the diameter of the AC508-150-A collimator (gluing lens) is 58 mm. The proposed optical model allows you to quickly calculate the parameters of optical elements and systems for the design of laser devices and such as shown Fig. 2.

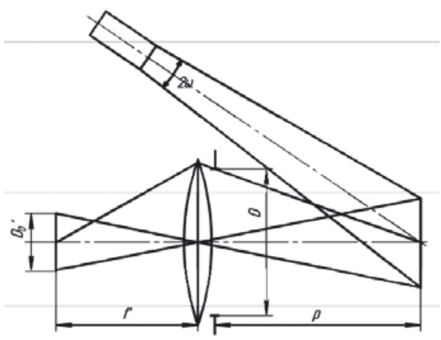

Fig. 1. The course of radiation rays reflected from the object surface

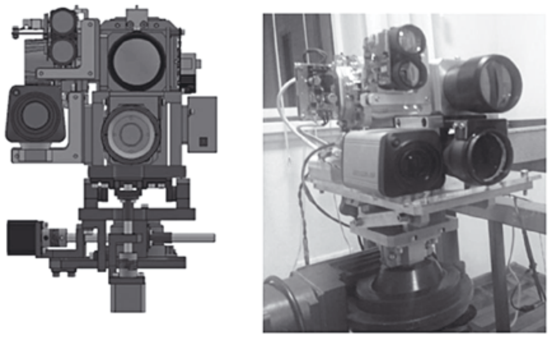

Fig. 2. The general structure and research model of laser optoelectronic systems for recognition of optical tools

THE PRACTICAL APPLICATION OF TOPOLOGY

Topology is the study of modal relations of spatial images, or of laws of connectedness, mutual disposition and traces of points, lines, surfaces, bodies and their parts or their unions in space, independently of relations of measures and quantities. Topology has proved to be an effective research theory of complex processes and objects. Modern topological analysis is considered as a prospective line of development of the research theory for nonlinear dynamic systems. It is a tool for evaluation Nonlinear Metrology [7—8] (NM). The NM task is a measurement of the complex dynamical systems parameters. As the examples of such systems can be the optical signals. Topological photonics is beyng, developed in recent years. It is a new line that studies the issue of the realization of topological effects in photonic crystals, coupled cavities, metamaterials and quasicrystals [9]. Topological methods are used for image evaluation [4].

There are the group of popular topological instruments that have demonstrated the high effective in the study of complex systems and optical signals. In the frame of NM such instruments as Lyapunov exponents, Shannon and Kolmogorov entropy, attractor and fractal dimension are used. These parameters can be used for researching and analysis of the optical signals with the complex structure and changing in time characteristics. Let's consider them.

Lyapunov exponents are used for study the dynamics of a system in the vicinity of an arbitrary trajectory. They characterize the degree of stretching and contraction of the phase portrait along the selected phase trajectories. If the two close trajectories $x_i(t)$ and $x_{i+1}(t)$ are chosen so that $x_{i+1}(t)=x_i(t)+\xi(t)$, $\xi(0)=\varepsilon, \varepsilon\to 0$ that the next function:

$$\Xi\left[\xi(0)\right]=\lim_{t\to\infty}\frac{1}{t}\ln\left[\frac{\xi(t)}{\xi(0)}\right] \quad (9)$$

takes a finite series of the Lyapunov exponents $\{\lambda_i\}, i=1,2,...,n$, the totality of which forms the Lyapunov spectrum. The number of Lyapunov exponents corresponds with the attractor dimension D_A, which can be fractional:

$$D_A = j+\sum_{i=1}^{j}\frac{\lambda_i}{|\lambda_{i+1}|}, \quad (10)$$

Here j is Lyapunov dimension, it is determined from the expressions:

$$\lambda_1+\lambda_2+...+\lambda_j>0,\ \lambda_1+\lambda_2+...+\lambda_{j+1}<0.$$

The total Lyapunov exponent Λ can be considered as an indicator of a stability of a system dynamics. When $\Lambda=0$ it is Hamiltonian system. It has a stable dynamic, the processes occurring in it can be regarded as deterministic processes, the volume of the phase portrait is unchanged $\Delta V_A=\text{const}$. When $\Lambda>0$ the phase portrait volume is growing $\Delta V_A\uparrow$, the dynamics is chaotic. If $\Lambda<0$ the phase portrait volume decreases $\Delta V_A\downarrow$, that typical for the dissipative systems.

For topological analysis of the systems the Shannon (*H*-entropy) and the Kolmogorov-Sinay (*K*-entropy) are used. *H*-entropy (or information entropy) is one of the key concepts of the information theory. For a system that can be in the states X_i with probability distribution density $p(X_i)$, Shannon entropy is given by the next formula:

$$H=-\sum_{i=1}^{N}p(X_i)\ln p(X_i). \quad (11)$$

Entropy is a measure of the order or disorder of the system. According to (11), The Shannon entropy assumes large values when the distribution density $p=p(X_i)$ has the values small. If a number of values N is bounded, then the entropy is maximal for the uniform distribution law $H\to\ln N$ for $p(X_i)\to 1/N$. The entropy is minimal $H\to 0$ for the normal distribution law when $p(X_i)\to 1$. The entropy of a strange attractor is higher than the entropy of a regular attractor. The entropy of chaotic and random dynamics is higher than the entropy of an ordered motion. The change of the *H*-entropy values indicates a change of dynamic.

The using the Kolmogorov entropy allowed us to introduce a rigorous criterion of chaotic, as an unstable by Lyapunov motion with positive metric entropy $K>0$. Analyzing the phase portrait of a system, the *K*-entropy is defined as:

$$K=\lim_{\substack{d(0)\to 0\\ t\to\infty}}\frac{\ln[d(t)/d(0)]}{t}, \quad (12)$$

where $d(0)$, $d(t)$ are the distances between two nearby trajectories at the initial and current time, respectively: $d(t)=|x_2(t)-x_1(t)|$.

According to (12) the *K*-entropy characterizes the degree of the trajectories divergence, and the degree of randomness of the system dynamics. It is related to the Lyapunov exponents (4) by the expression:

$$K=\int\sum_{\lambda_i\geq 0}\lambda_i(x)d\mu. \quad (13)$$

The fractal dimension is a main characteristic of such structure as a fractal. According to B. Mandelbrot, a fractal can be defined as an object for which the Hausdorff-Besicovitch dimension (the fractal dimension *D*) strictly exceeds the topological dimension [10].

Fractal signs can be found in the structure of signals and fields, behavior of functions that evaluate the distribution of physical quantities in time and space during the physical research. It follows that it would be possible to search for a fractal dimension as a special characteristic of processes or images.

The method of rescaled range that is empirically derived by *P*. Hurst is used to compute the *D* series $\{x_i\}$ (where $\{x_i\}$ is the value of a quantity *x*, i = 1,…, *n*) [9—15].

Evaluation of the series $\{x_i\}$ allows us to calculate the Hurst exponent Hr associated with D:

$$D = 2 - Hr. \tag{14}$$

The values of the Hurst exponent vary between $0 \le H \le 1$ and are determined by the ratio R/σ, where: R — the span between the maximum and minimum values of the increment function $x(I, n)$, σ — the standard deviation:

$$\left.\begin{aligned} R(i) &= \max_{1\le i\le n} x(i,n) - \min_{1\le i\le n} x(i,n); \\ x(i,n) &= \sum_{i=1}^{n}\left(x_i - \bar{x}_i\right) \end{aligned}\right\} \tag{15}$$

where $\bar{x}_i$ — the mean $\{x_i\}$.

The ratio R/σ is related to the parameter Hr as follows:

$$R/\sigma = (n/2)^{Hr} \tag{16}$$

By using (14)—(16) it is possible to obtain the value of the fractal dimension for both the entire observation interval or its selected areas as well as to determine the dynamic characteristic of x for both selected time spans or during the observation time on the whole. To classify the dynamics of x, a fractal scale is created with points 1, 1.5, 2: at $D = 1$ when the dynamics of x is strictly determined; at $D = 2$, when the value of x behaves in a regular manner , but the range of the measured values is very large; at $D = 1{,}5$ the dynamics of x is random. If $1 < D < 1{,}5$ or $1{,}5 < D < 2$, then the process in question is non markovian, random, persistent and antipersistent, respectively.

Knowledge of the fractal dimension of the D series $\{x_i\}$ allows us to evaluate the behavior of the measuring object (or signal structure) and to select the appropriate mathematical tool for processing the measurement results.

TOPOLOGICAL RECOGNITION OF OPTICAL SURVEILLANCE DEVICES

The topological model of optical surveillance devices (OSD) recognition which is based on fractal insights about the structure of signals can be proposed. Consider LOS which operates under procedure: the laser pulse propagates in the direction of the possible OSD, and then it reflects from the surface of an object and returns back. The aim of LOS is to determine the coordinates of the reflective surface and recognize it. Consider the issue of object recognition, leaving out of scope of this paper the issue of the coordinate determination of an object by means of optical methods. The aim of recognition arises from the need to detect OSD against the background of possible «false» targets with reflective surfaces.

A special feature of OSD is that the refractive and reflective surfaces of optical parts are coated with thin films of various material substances, such as metals and their oxides, dielectrics, silicon, etc. This makes it possible to change the optical characteristics of the parts and give them new physical properties. The lenses of binoculars, photo and video cameras are coated with antireflection coatings, the material and thickness of which are chosen such as to be able to transmit the visible radiation. The waves for which the condition is fulfilled are practically not reflected:

$$\lambda = 4dn, \tag{17}$$

where d — the film thickness, n — refraction index.

In the case of a multilayer coating, we consider the wavelength range $[\lambda_{min}; \lambda_{max}]$ specified by the condition (17). Radiation with wavelengths that do not fall within this range is reflected. In such case, due to the overlapping of radiation reflected from different layers of the coating, interference in the reflected beams is observed [13—18].

The presence of signal interaction traces with the antireflection coating in the reflected optical signal leads to the possibility of OSD recognition. The study object would be a cross-sectional area of a laser beam reflected from a surface covered with a thin film. Evaluation of the beam's cross-sectional area is performed by using a CCD camera with a linear lens which is included in LOS. The camera makes it possible to study the distribution of radiation intensity along the selected axis on the plane (x, y) [17—20].

The intensity distribution in the interference image is approximated as follows:

$$I_{\text{Int}}(x) = I_0 \cos^2(kx), \tag{18}$$

where I_0 — maximum intensity, k — wavenumber [11].

The intensity distribution function $I(x)$ (18) is subject to fractal analysis (14)—(16). Consider the case of a linear intensity distribution: $I(x) = I_0 \times j$, where j — intensity measurement number, $j = 1\ldots m$.

The span of R and dispersion of σ computed for the increment function as follows:

$$R = \frac{I_0}{8} m^2,\ \sigma = \frac{I_0}{2\sqrt{3}} \sqrt{m(m+1)} \tag{19}$$

It follows from the equation (16):

$$H = \ln(R/\sigma)/\ln(m/2). \tag{20}$$

Dependence of R/σ on m looks like this:

$$\ln(R/\sigma) = \ln\left(\sqrt{3}/4\right) + \ln(m) + \ln(1 - 1/2m) \tag{21}$$

Substituting (21) into (20) we obtain that for a straight line and large readings:

$$H = \lim_{m\to\infty}\left[\ln(R/\sigma)/\ln(m/2)\right] = 1. \tag{22}$$

Consequently, the value of the fractal dimension (14) $D = 1$. A similar result can be obtained for any smooth curve, for example, for a sinusoid with a period that is commensurate with m. When analyzing actual signals presented in the form of two-dimensional plots $I(x)$, the parameter D describes the degree of ruggedness of a plot $I(x)$: at high values of D the plot looks too rugged, but at low values of D the plot looks softer. The equation (18) describes a smooth and continuous curve. According to (19)—(22), the fractal dimension of function (18) is equal to 1. However, the signal in real conditions will get into the CCD lens in a form different from (18) as a result of the effect of intensity noise $I_N(x)$. Assuming that the link between signal and noise is of an additive character, we will present the resulting signal $I_{Rez}(x)$ as follows:

$$I_{Rez}(x) = I_{\text{Int}}(x) + I_N(x). \quad (23)$$

This will increase the value of the fractal dimension by ΔD. Due to the stochastic nature of noises, their fractal dimension is higher than the fractal dimension of the desired signal. Experiments show that the fractal dimensional increment ΔD is 0,1—0,3 with a signal-to-noise ratio $q_0^2 = -3$ dB [4]. Therefore, the value of the fractal dimension of the signal (23) can be estimated as $1{,}1 \le D \le 1{,}3$. When a pulse is reflected from the surface without an antireflection coating, there is no interference component in the signal (23), and the signal will be stochastic, for which $D = 1{,}5$.

The fractal dimension is not the only tool of fractal analysis and it is capable of answering a limited range of issues; in the framework of the general task is the recognition of OSD. It is not enough to address the issue of OSD type. The group of the fractal characteristics of a specific OSD must be developed in order to recognize and classify OSD. Fractal characteristics together with the fractal dimension must include the type of fractal signatures, the type of spatial spectrum and the values of spatial frequency that characterize the signal structure.

OSD RECOGNITION SYSTEM SCHEME

The developed topological model of OSD recognition (6)—(15) is used in the system of OSD recognition developed by the laboratory «Photonics».

The laser radiation from the source (probe beam) gets into the lens of the OSD. Some part of the incident laser radiation is reflected from the lens's anti-reflection film and returns to the system. The recognition system of OSD uses laser emitters in the near-IR range to ensure that the operator of OSD could not see that he was detected. Note that the human eye has almost zero sensitivity to radiation with a wavelength of more than 700 nm. This wavelength is actually used in laser optics detection systems in order to be invisible.

Integration of an infrared camera in the recognition system of OSD allows us to see an intense spot of light on a computer screen or a display and to record an optical device and the like. The laser unit for distance measurement and the unit for determining the coordinates of the reflected signal (equipped with a magnetic compass and a GPS receiver) make it possible to determine the distance to the OSD and its coordinates. The topological recognition model developed by the authors (6)—(15) allows identifying the type of OSD.

CONCLUSION

The paper presents the system for detection and recognition of hidden optical surveillance systems. The main algorithm of system is based on fractal insights about the structure of the optical signal and determination of the fractal dimension intensity distribution in a cross-sectional plane of the laser pulse reflected from the target. It is shown that the approximation of the fractal dimension value to unity is a prerequisite to the target classification as an optical surveillance device.

In order to classify the type of an optical device along with the fractal dimension the group of the fractal characteristics, consisting of the type of fractal signatures, the type of spatial spectrum and the values of spatial frequency that characterize the signal structure must be developed.

Recognition system of optical surveillance devices is based on the topological model of optical surveillance devices recognition. It allows measuring the distance and coordinates of a target as well as recognizing it.

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