Study of the Adaptive Method of Approximation of Experimental Data

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Abstract

In today's world, information has become not only data but also a weapon. To obtain access to information, not only legal but also illegal methods of obtaining it are used. Illegal methods can be used to secretly obtain information. Which transmits the information received over the radio channel. Moreover, criminals use different methods of transmission, to hide a useful signal. It is very difficult to detect the signal. To detect such signals, various methods and techniques are used, which make it possible to convert a random signal into a digital form or to approximate the signals. For further digital processing of the received information. This article proposes adaptive algorithms for signal approximation of random radio signals based on the continuous gradient method. The main goal of the method is to determine the vector of parameters in the basis functions so that they approximate the signal. The convergence analysis of the iterative procedure is based on the direct Lyapunov method. In most cases, as a rule, the signals of means of tacitly obtaining information are measured at discrete moments. Unfortunately, there are many cases in which this leads to an error in detecting the signals of means of obtaining information secretly. Therefore, the detection of continuous signals is an urgent task. This work is devoted to the solution of this urgent task. The methods proposed in the work are described for the approximation of continuous processes. In this case, we recommend using well-known computational methods to find a solution to the Cauchy problem. This makes it possible to obtain a discrete form of the developed methods. A continuous variant of the methods solves the actual task of identifying the means of covertly obtaining information and can be universal in general.

In order to confirm the adequacy of the developed method and to confirm the effectiveness of the developed mathematical apparatus. An experimental study was conducted, which confirmed the adequacy of the developed method.

Keywords

object of critical infrastructure, object model, robust system, disturbance transitional process

1. Introduction

In the conditions of rapid development of information technologies and growth of data volumes, computer networks have become an integral part of modern life and business processes. Their efficiency, reliability, and security depend on the stability and productivity of organizations, as well as the protection of users' confidential information. An important component of network management is the procedure for providing access, which determines how and who can access network resources, as well as how to ensure their security and integrity. Information is one of the most valuable assets of most modern companies. As the value of information increases, so does the number of those who wish to obtain this information for use in their own or others' interests.

One of the ways to obtain information is to intercept or record speech information using means of tacit information.

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There is a huge arsenal of various means of interception and recording of acoustic information. The use of certain means of acoustic control depends on the conditions of use, the task, the technical, and, above all, the financial capabilities of the audition organizers. The most common are radio-emitting means of interception of speech information. The variety of radio microphones is so great that there is a constant need for new methods of detecting radio microphone radiation signals.

Therefore, the methods of detecting radio microphone signals are constantly being improved.

Information protection is a complex process. Various technical devices are used to intercept and record confidential information. Most of these devices transmit the intercepted or recorded speech information using a radio channel. Therefore, the main thing in this case is the detection of the radio channel by means of covertly obtaining information. One of these methods can be the adaptive method of approximating experimental data of the spectrum of means of tacitly obtaining information. A necessary condition for information protection is the blocking of all technical channels of leakage or unauthorized access to confidential or secret information.

The topicality of the topic is due to the growing complexity and scale of information networks. The increase in the number of users and devices connecting to information networks complicates the task of ensuring proper access control and protection of information systems from unauthorized access. Thus, a contradiction arises between information network protection systems and new information technologies in conditions of limited time and an increase in the number of attempts to obtain information through covert information. This work is devoted to solving this contradiction.

Review of literary sources.

The problem of signal conversion is a very urgent problem of our time. This problem exists in all areas of our lives. This problem becomes especially acute in the modern world when the pace of life has increased significantly and there are problems with obtaining data quickly. The problem of saving valuable information constantly arises. Protection against secret receipt. For covertly obtaining information, various means of covertly obtaining information are used based on the principle of operation and design. There are different signals by means of which information goes beyond the control zone. Digital methods are always used to increase the speed of data processing. But the signals from the means of tacitly obtaining information are of a diverse nature. Therefore, there is a problem of converting such signals into digital form with further processing by technical computing devices. Currently, the problem of approximation of a continuous and discrete signal is one of the important problems of signal processing theory. This problem is covered in many books and articles [1-7]. However, new applied problems require the development of new methods. Methods should be simple, provide real-time solutions, and have optimal performance. One of the approaches that allows you to meet the requirements is an adaptive technique [5-7]. Adaptive methods are effective in the tasks of signal processing, optimization, control, and identification of parameters [5-12]. For signal processing problems, we recommend a structural approach [7, 20, 21]. This means that we approximate the signal with a function that depends on unknown parameters. Approximation of the signal is carried out adaptively using the appropriate selection of parameters. For this, we will use the continuous gradient method [13, 16-19,23]. This approach can be conveniently applied to both continuous and discrete signals. To prove the convergence of the corresponding iterative methods, it is possible to use the methods of the stability theory [14-16,25]. We apply an adaptive procedure to the problems of chemical-biological analysis based on spectral data, in particular to the problem of spectral processing of data from plants contaminated with chemical elements.

Thus, on the basis of the conducted analysis, the results of the study of scientific publications on the topic of research, dissertations, patents, monographs and practical developments, it was established that at the current stage of the development of progressive information technologies there is an objective contradiction between the systems of protection of information networks and news information technologies in the conditions limited time and an increase in the number of attempts to obtain information by covert means of obtaining information. This work is devoted to the solution of this actual contradiction.

Formulation of the problem

To obtain access to information, not only legal but also illegal methods of obtaining it are used. Illegal methods can be used to secretly obtain information. Which transmits the received information over the radio channel. It is very difficult to detect the signal. Therefore, it is necessary to develop and propose a method of increasing the detection of signals by means of surreptitiously obtaining information in the spectrum of a specified radio range due to the use of an adaptive technique for approximating the signal based on the continuous gradient method and evaluating the scalar continuous signal with a function that depends on time and unknown parameters.

The main section

Approximation of continuous signals.

Suppose that we have a continuous scalar signal $x=\varphi(t),\ \ t_0 \le t \le T$, which we approximate with a function

$$x(t) \approx \psi(t,\alpha) = \psi(t,\alpha_1,\alpha_2,...,\alpha_n) \tag{1}$$

If the signal is defined on $[t_0, t]$, the problem of parameters α adaptive correction consists of a functional minimization [21,22]. For this purpose, we consider two types of functionals:

a) directly at the moment t

$$I_1(t) = (\psi(t,\alpha) - \phi(t))^2; \tag{2}$$

b) mean square approximation on $[t_0, t]$

$$I_2(\alpha) = \int_{t_0}^{t} (\psi(\tau,\alpha) - \phi(\tau))^2 \, d\tau. \tag{3}$$

To correct parameters we minimize functional (2), as a result we write down continuous gradient method [13,20]

$$\frac{d\alpha}{dt} = -grad_a I_1(\alpha) = -2(\psi(t,\alpha) - \phi(t)) grad_a \psi(t,\alpha) \tag{4}$$

with some initial data

$$\alpha(t_0) = \alpha^{(0)}. \tag{5}$$

To find vector parameters α we solve Cauchy problems (4), (5). If there is a stationary problem solution (4), (5), that is $a(t) \to \tilde{a},\ \ t \to \infty$, you can be taken as a solution of a given problem. It is necessary to notice that for solving some practical problems such a simple procedure gives good results.

For the integral functional (3) we write down likewise a system of ordinary differential equations

$$\frac{d\alpha}{dt} = -grad_a I_2(\alpha) = -2\int_{t_0}^{t} (\psi(\tau,\alpha) - \phi(\tau)) grad_a \psi(\tau,\alpha) d\tau. \tag{6}$$

The right part of a system (6) is an integral. Taking derivatives of both parts of the system (6), we have

$$\frac{d^2\alpha}{dt^2}=-2(\psi(t,\alpha)-\phi(t))grad_a\psi(t,\alpha). \tag{7}$$

System (7) is a system of ordinary differential equations of order $2n$, in normal form with initial conditions

$$a(t_0)=a^{(0)},\ \ \frac{da(t_0)}{dt}=0. \tag{8}$$

One solves problems (4), (5) and (7), (8) numerically, for instance, with Runge-Kutta's method. As in the previous case, if there is a limit $a(t)\to\tilde{a},\ \ t\to\infty$, when solving (7), (8), it can be taken as a solution to the given problem.

Comment 1. The original data is to be chosen from the convergence of the proposed iterative procedures.

Convergence of iterative procedures can be investigated on the basis of Lyapunov second method. Therefore, parameter $\alpha^{(0)}$ we will choose from the range of asymptotic stability of an appropriate system of ordinary differential equations. If conditions of Barbashin-Krasovsky theorem on global asymptotic stability take place, the convergence of iterative procedures is fulfilled for any initial data $\alpha^{(0)}\in E^n$ [14, 15, 27].

Consider a particular case. Suppose we have a system of basic functions:

$$\phi_1(t),\ \ \phi_2(t),...,\phi_n(t),\ \ t\geq t_0, \tag{9}$$

and function $\psi(t,a)$ is a linear combination of basic functions

$$\psi(t,\alpha)=\sum\nolimits_{j=1}^{n}\alpha_j\phi_j(t). \tag{10}$$

In this case we get system of ordinary differential equations (4) as follows:

$$\frac{d\alpha_i}{dt}=-2(\sum\nolimits_{j=1}^{n}\alpha_j\phi_j(t)-\phi(t))\phi_i(t),\ \ i=1,2,...,n. \tag{11}$$

System (11) can be written this way:

$$\frac{d\alpha_i}{dt}=-2\phi_i(t)(\sum\nolimits_{j=1}^{n}\phi_j(t)\alpha_j+2\phi(t)\phi_i(t),\ \ i=1,2,...,n. \tag{12}$$

one can observe that (12) is a linear non-homogeneous system of differential equations in the form

$$\frac{d\alpha_i}{dt}=A(t)\alpha+f(t),\ \ t\geq t_0. \tag{13}$$

Here

$$\alpha^T=(\alpha_1,\alpha_2,...,\alpha_n),f^T(t)=2\phi(t)(\phi_1(t),\phi_2(t),...,\phi_n(t)),$$

$$A(t)=\begin{pmatrix} -2\phi_i^2(t) & -2\phi_1(t)\phi_2(t)\cdots & -2\phi_1(t)\phi_n(t) \\ -2\phi_1(t)\phi_2(t) & -2\phi_2^2(t) & \cdots -2\phi_2(t)\phi_n(t) \\ \cdots & \cdots \quad \cdots & \cdots \\ -2\phi_1(t)\phi_n(t) & -2\phi_2(t)\phi_n(t)\cdots & -2\phi_n^2(t) \end{pmatrix}$$

is a symmetric matrix of dimension $n \times n, T$ means the sign of transposition.

According to Cauchy formula the solution to problems (5), (13) can be written as follows [16]

$$\alpha(t)=W(t,t_0)\alpha^{(0)}+\int_{t_0}^{t}W(t,\tau)f(t)d\tau, \tag{14}$$

where $W(t,\tau)$ denotes the fundamental matrix of the homogeneous system corresponding to (13) and normed at the moment τ i.e.

$$\frac{dW}{dt}=A(t)W,\quad W(\tau,\tau)=E_n. \tag{15}$$

Similarly one can find a system of differential equations for functional (3) provided (10). In this case, system (6) can be written in this form:

$$\frac{d\alpha_i}{dt}=-2\int_{t_0}^{t}\left(\sum_{j=1}^{n}\alpha_j\phi_j(\tau)-\phi(\tau)\right)\phi_i(\tau)d\tau,\quad i=1,2,\ldots,n. \tag{16}$$

System (16) is a linear system of integral-differential equations. Using (7) such a system can be rewritten this way

$$\frac{d^2\alpha_i}{dt^2}=-2\left(\sum_{j=1}^{n}\alpha_j\phi_j(t)-\phi(t)\right)\phi_i(\tau),\quad i=1,2,\ldots,n. \tag{17}$$

Linear system (17) could be written in a vector-matrix form

$$\frac{d\tilde{\alpha}}{dt}=\overline{A}(t)\tilde{\alpha}+2\overline{f}, \tag{18}$$

where $\tilde{\alpha}^T=\left(\alpha^T,\dfrac{d\alpha^T}{dt}\right)$, $\overline{f}^T(t)=(0^T,f^T(t))$ are vectors of dimension *2n*, $\overline{A}(t)=\begin{pmatrix}0 & E_n\\ A(t) & 0\end{pmatrix}$, is a matrix of dimension $2n \times 2n$ with known elements.

However, to find a solution to system (18) one should consider a linear system of ordinary differential equations (18) with Cauchy conditions (8). Using Cauchy formula we can write the solution of system (18) for any initial conditions in the form [16]^

$$\tilde{\alpha}(t)=\overline{W}(t,t_0)\tilde{\alpha}(t_0)+\int_{t_0}^{t}\overline{W}(t,\tau)\overline{f}(\tau)d\tau \tag{19}$$

where $\bar{W}(t,\tau)$ is normed at a moment τ fundamental matrix of a homogeneous system:

$$\frac{d\tilde{\alpha}}{dt} = \bar{A}(t)\tilde{\alpha}. \tag{20}$$

This matrix satisfies the matrix differential equation with initial conditions in the form

$$\frac{d\bar{W}}{dt} = \bar{A}(t)\bar{W}, \quad \bar{W}(t_0,t_0) = E_{2n}. \tag{21}$$

We rewrite formula (20) taking into account the structure of the vectors $\bar{\alpha}, \bar{f}$ and represent the matrix $\bar{W}$ in structural form

$$\bar{W}(t,\tau) = \begin{pmatrix} W^{(1,1)}(t,\tau) & W^{(1,2)}(t,\tau) \\ W^{(2,1)}(t,\tau) & W^{(2,2)}(t,\tau) \end{pmatrix}$$

where $W^{(i,j)}(t,\tau)$ is a matrix of dimension n. In this case we have:

$$\alpha(t) = W^{(1,1)}(t,t_0)\alpha^{(0)} + \int_{t_0}^{t} W^{(1,2)}(t,\tau) f(\tau) d\tau \tag{22}$$

$$\frac{d\alpha}{dt} = W^{(2,1)}(t,t_0)\alpha^{(0)} + \int_{t_0}^{t} W^{(2,2)}(t,\tau) f(\tau) d\tau. \tag{23}$$

Formula (22), (23) show that in order to find and analyze the parameters vector we need only (22). (23) is necessary for evaluating the field of convergence of iterative procedures (18) under initial conditions.

In some cases, for example, to determine a stationary mode of change of vector $\alpha(t)$, we need to set a boundary conditions for derivative:

$$\frac{d\alpha(T)}{dt} = \alpha^{(1)}. \tag{24}$$

Then, using (24) and (23) one can find the appropriate initial data providing

$$\alpha^{(0)} = W^{(2,1)^{-1}}(T,t_0)\left[\alpha^{(1)} - \int_{t_0}^{T} W^{(2,2)}(T,\tau) f(\tau) d\tau\right]. \tag{25}$$

In this case, solution (22) can be written as follows:

$$\alpha(t) = W^{(1,1)}(t,t_0)W^{(2,1)^{-1}}(t,t_0)\left[\alpha^{(1)} - \int_{t_0}^{T} W^{(2,2)}(T,\tau) f(\tau) d\tau\right] + \int_{t_0}^{t} W^{(2,2)}(T,\tau) f(\tau) d\tau. \tag{26}$$

Analysis of iterative procedures convergence

Let us analyze the convergence of iterative procedures using Lyapunov methods [4]. Consider two types of functionals (2) and (3).

Case 1. Let us consider the iterative scheme based on the minimization of function (2). Suppose that the solution of Cauchy problem (5), (13) meets the condition $\alpha^{(1)}(t,t_0,\alpha^{(0)}) \to \bar{\alpha} = const, \quad t \to \infty.$ Then substituting:

$$\alpha = \alpha^{(1)}(t,t_0,\alpha^{(0)}) + \nu(t) \tag{27}$$

we come to a homogeneous system of linear differential equations with respect to new variable $\nu(t)$

$$\frac{d\nu}{dt} = A(t)\nu, \quad t \ge t_o. \tag{28}$$

Then under the assumption that the original data (5) can be perturbed, the convergence of iterative procedure (13) is equivalent to the stability of the solution $\nu(t) \equiv 0, \quad t \ge t_0$ of linear homogeneous systems (28). The following theorem is true.

Theorem 1. For the convergence of iterative scheme (13) under perturbed initial data:

$$\alpha(t,t_0,\alpha^{(0)} + \nu^{(0)}) \to \bar{\alpha}, \quad t \to \infty \tag{29}$$

it is necessary and sufficient that the following condition holds:

$$W(t,t_0) \to 0, \text{ for } t \to \infty. \tag{30}$$

The proof of theorem 1 is based on representation (27), uses the condition of asymptotic stability of homogeneous linear systems of differential equations in terms of fundamental matrix and homogeneous system (28) solution representation by Cauchy formula [16, 29]

$$\nu(t) = W(t,t_0)\nu^{(0)}. \tag{31}$$

Here $\nu^{(0)}$ is the *n*-dimensional vector of initial data for a homogeneous system (28), $\bar{\alpha}$ is the *n*-dimensional stationary vector, which gives the solution to the problem.

Comment 2. One can observe that under theorem 1 conditions convergence of iterative procedure takes place for any initial data, i.e., in general. It follows from the fact that the asymptotic stability of homogeneous linear systems is always global.

Detection of chemical components in the plants and calculation experiment

In this section, we consider the problem of spectral data processing of plants contaminated with chemical elements and apply the technique offered in previous sections. We assume that plant pollution is generated by some chemical elements and the spectral data received. They are considered as basic for the recognition of new experimental data. Let us designate basic spectral functions:

$$\phi_1(t), \phi_2(t), \ldots, \phi_n(t), \quad t_0 \le t \le T, \tag{32}$$

which represent the spectral data of plant pollution by known chemical elements.

Let $\phi(t), \ t \in [t_0, T]$ be the measured spectral function contaminated by an unknown chemical element. The function $\psi(t,\alpha)$ is chosen as a linear combination of (10) $\psi(t,\alpha) = \sum_{j=1}^{n} \alpha_j \phi_j(t)$. Consider a system of ordinary differential equations (11)

$$\frac{d\alpha_i}{dt} = -2\left(\sum_{j=1}^{n} \alpha_j \phi_j(t) - \phi(t)\right)\phi_i(\tau), \quad i = 1, 2, \ldots, n. \tag{33}$$

Let us write it in form (33):

$$\frac{d\alpha}{dt} = A(t)\alpha + f(t), \quad t \in [t_0, T]. \tag{34}$$

In the case of discrete signals, the solution of system (13) can be represented as following:

$$\alpha(i+1) = \alpha(i) + \left(A(t_i)\alpha(i) + f(t_i)\right)\Delta t), \quad t \in [t_0, T], \tag{35}$$

where $\Delta t = t_i - t_{i-1}$ is the quantization of time.

Depending on type of experimental data to improve the detection of signs of chemical contaminants contribution it is needed to hold some mathematical conversions. In Particular:

- for each selected discrete basic function (with the main chemical pollution) a new basis is built, which is the difference of functions of the old basis and explored experimental data;
- over discrete basic functions and experimental data under investigation it is advisable to make discrete Fourier transforming [1-4,28] and assume them as a new converted basic and experimental data under investigation.

Numerical experiment conducted under the described above adaptive algorithm. Spectral experimental data on a plant specimens were chosen for the basic functions, which were contaminated by the chemical elements $CaCl$ and $K_2Cr_2O_7$. Spectral values of basic functions are displayed on Figure 1. For the recognition of new experimental data for the contamination with selected chemical elements, an adaptive algorithm is applied and the result are shown on Figure 2.

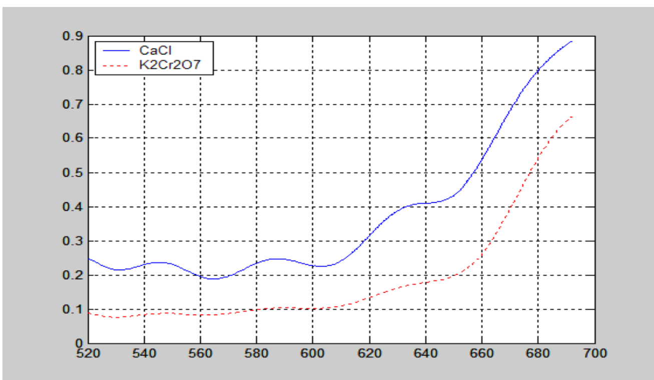

Figure 1: Spectral values of basic functions

The unknown parameters vector converges to 0 for the experimental data contaminated by $CaCl$ and to 1 for those contaminated by $K_2Cr_2O_7$ correspondingly. It means that contamination by chemical element $K_2Cr_2O_7$ is recognized.

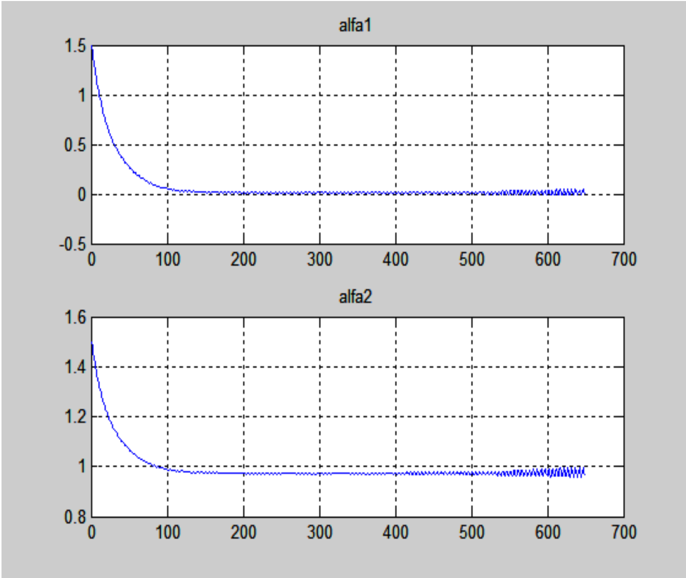

Figure 2: Iterative procedure convergence for experimental data contaminated by the chemical elements $CaCl$ (alfa1) and $K_2Cr_2O_7$ (alfa2)

Conclusion

Information protection is a very complex process. Various technical devices and means are used to intercept and record confidential information. Most of these devices transmit intercepted information using a radio channel. The main thing in this matter is the detection of a signal in the radio range spectrum, which is used by the means of covertly obtaining information. One of these methods can be the adaptive method of approximating experimental data of the spectrum of means of tacitly obtaining information.

The method proposed in the paper uses an adaptive technique for signal approximation based on the continuous gradient method. We evaluate a scalar continuous signal with a function that depends on time and unknown parameters. The paper proposes two main algorithms corresponding to two main functional describing the difference between a signal and a parametric function. This makes it possible to significantly increase the probability of detecting signals of means of covertly obtaining information, which will allow blocking the unauthorized channel of information leakage. And in general, improve information protection.

Considered a special case when the parametric function is a linear combination of the basic function. The iterative procedure of convergence analysis is based on the second Lyapunov method. Which proves the scientific novelty of the work.

Theoretical conclusions and proposed algorithms are confirmed experimentally.

Thus, the goal of the work has been achieved.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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