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Article

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APPLICATION OF THE ASSOCIATIVE RECOVERY METHOD IN THE CHALLENGES OF INCREASE INFORMATIVITY OF DISTORTED IMAGES AND DETECTION OF MINOR CHANGES IN STORED SAMPLES

The object of research is optical-electronic methods and related digital information processing. One of the most problematic areas is the reconstruction of missing parts of the stored data and the inability to detect minor changes in the stored samples, as well as the reconstruction of the entire corrected template from its incomplete version.

As part of the study, a correlation-optical approach to the problem of holographic associative memory was used, which made it possible to achieve highly efficient heteroassociative reconstruction of the entire corrected template from its incomplete version. The analysis of hologram models with phantom images and nonlinearly recorded holograms read in the associative mode shows a wide range of useful possibilities. It is primed not only in the tasks of reconstruction of data, but also in the case of insignificant changes in savings, highly effective heteroassociative reconstruction based on a non-interference mechanism. The analysis of the results of the correlation-optical approach to the problem of holographic associative memory shows that the described method opens up additional opportunities for solving the problems of detecting small changes in the object scene, which is important, in particular, for early registration of events and phenomena. It is related to the fact that the detection and localization of changes is carried out according to the difference in intensity across the image field (the effect of brightness inversion in the phantom image of referenceless hologram): the brightness of the image of the changed area is higher, and to a greater extent, the smaller the changes compared to the reference image. It should be especially noted that the specified properties of the nonlinear-holographic associative memory are realized not algorithmically, but physically, taking into account the fundamental nonlinearity of all natural processes, which is neglected when conducting a superficial (in the first approximation) analysis. Physical modeling of associative memory based on second-order holograms does not involve any circuit complications compared to the standard holographic procedure.

Keywords: *holographic associative memory, hologram models, associative information recovery, physical modeling.*

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1. Introduction

In recent decades, there has been an active development of methods and means of pattern recognition. Information technologies and intelligent information systems are being improved, in which the end recipient of information is a person. A promising direction of scientific research in this area is the improvement of intelligent visual image recognition systems and related methods for storing and updating information. In this regard, more and more researchers are considering the latest methods of supporting machine intelligence, the development of which is impossible without the improvement of memory systems. In this sense, the studies of Chinese scientists devoted to the introduction of new methods of using machine intelligence and the prospects for their application in neurocomputing systems are interesting [1]. Successful research in this area has resulted in a modern artificial intelligence system (ALSTM) based on attention mechanisms and long short-term memory (LSTM) applied in end-to-end differentiated neural networks to achieve complex considerations [2].

An innovative approach based on deep learning of the neural network CNN-LSTM (convolutional neural network, long short-term memory), which can serve as the basis for the use of recognition methods in computer vision systems outlined in the studies [3].

Deep learning algorithms have also been successfully applied to fiber endoscopy. In [4], Swiss researchers show that deep neural networks (DNNs) can be a versatile technique for classifying and reconstructing input images. A comparison between holographic recording and intensity-only speckle output used as input to a DNN shows that high performance can be achieved without full field information (amplitude and phase). Astonishing reconstruction

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accuracy and classification accuracy of fiber input data from images of speckle intensity alone is reported. Interesting methods of holographic recording and reproduction of information in crystals are presented in [5].

So, holography today is a new innovative technology that can completely transform the use of digital technologies in new cybernetic systems. Holographic technologies can increase the efficiency of existing products and services in many technology sectors such as architecture, 3D modeling, robotics, healthcare and medical engineering [6, 7].

All of the above predetermines the relevance of this study, the object of which is optoelectronic methods and the digital processing of information associated with them. The aim of the study is to generalize the capabilities of holographic associative memory (HAM) in terms of optical storage and information retrieval. As part of this, the circumstances that prevent the widespread use of this attractive approach for optical data processing will be clarified. HAM is considered here as a promising optoelectronic method of digital information processing. The main advantage of the described method is that it is able to provide physical modeling of associative memory, which is especially useful in the problems of high-quality information recovery from an incomplete version and in early registration of events and phenomena.

2. Research methodology

At the present stage, optical and optoelectronic methods for processing and increasing the information content of space images have been developed. One of the promising methods described in this study is the correlation-optical method, which is advisable to use to detect small changes in the object scene in the case of undistorted images.

During the implementation of this study, the possibility of physical modeling of the process of recognition of complex images and their updating according to the associative principle is substantiated. The image can be reproduced even if its contrast is increased. This is the main advantages of physical modeling of associative restoration of information arrays (images) with enhanced information characteristics (error correction) by means of static nonlinear holography. Thus, optoelectronic methods and the digital processing of information associated with them currently have no alternatives.

3. Research results and discussion

3.1. Optical correlation model of phantom holographic images. Let's consider phantom holographic images within the framework of the linear approximation of the theory of holography [8]. The amplitude permeability of a thin reference hologram is equal to:

$$T_a = T_0 + T_E = T_0 + T_1 \sum_{q=1}^{N} \alpha_q \sum_{p=1}^{N} \alpha_p^* =$$
$$= T_0 + T_1 \left(\sum_{q=p=1}^{N} |\alpha_q|^2 + \sum_{q \neq p=1}^{N}\sum^{N} \alpha_q \alpha_p^* \right), \quad (1)$$

where T_0 – the initial transmittance; T_E – the transmittance to exposure; the term from T_1 describes the exposure-dependent part of the amplitude transmission; α_q – the angle at which the restoring light beam propagates from the q-th repeater; α_p – the direction of propagation of the reference beams; α_p^* – the reduced α_p values, taking into account the change in the angle of inclination of the stripes of the hologram structure. The first sum in brackets describes the average field strength of the object above the registration plane (as in the absence of interference/coherence among repeaters), while the second double sum corresponds to the set $N(N-1)/2$ of intermodulation grating recorded by all possible pairs – repeaters of the object. Let's read a referenceless hologram with amplitude transmission (1) over the object field:

$$\{T_a\} G = T_0 \sum_{q=1}^{N} \alpha_q + T_1 \left\{ \sum_{q=1}^{N} \alpha_q \sum_{p=1}^{N} \alpha_p^* \right\} \sum_{j=1}^{N} \alpha_j =$$
$$= \left[T_0 + T_1 \left(\sum_{j=p=1}^{N} |\alpha_j|^2 \right) \right] \sum_{q=1}^{N} \alpha_q + T_1 \left(\sum_{j \neq p}^{N}\sum^{N} \alpha_p^* \alpha_j \right) \sum_{q=1}^{N} \alpha_q \equiv$$
$$\equiv \left(T_0 + T_1 |G|^2 \right) G + T_1 G G^* G, \quad (2)$$

where G – the field of the object; α_j – the angle (direction) of propagation of halo rays.

The first term on the right side of equation (2) describes the superposition of two fields, namely zero and first order diffraction, corresponding to the reconstruction of the entire stored pattern by each of the object's repeaters as «local» quasi-point reference sources. The second term corresponds to the convolution of the stored template with its autocorrelation image (in the reconstruction domain, which is the Fourier transform of the corresponding filtering, i. e., the hologram domain). The last double convolution describes a halo near the reconstructed image, caused by the expansion of the object, which is the reference point [9].

3.2. Characteristics of brightness of an image reconstructed by a hologram of a phantom image. Let's turn to the two points under equation (2). First, the plus sign in (2) has a different content for three cases: negative amplitude, positive amplitude and phase hologram. It should be noted that this difference is of no importance in conventional out-of-balance holography. Since the main and merged images are reconstructed outside the readout beam, additional diffraction devices generate the same diffraction patterns (intensity distribution in the image area), according to Babinet's principle. In contrast, in phantom image holography, two object fields (zero and first diffraction orders) are not separated by angle and, as a result, overlap. For an amplitude positive hologram, the phantom image, the two mentioned fields are phase fields; for a phase hologram, these fields are added «in quadrature» (with a phase difference of $\pi/2$). But in the most straightforward case of negative amplitude of the hologram, the two superimposed fields are in opposite reflected phases, so that equation (2) is rewritten as:

$$\{T_a\} G = \left(T_0 - T_1 |G|^2 \right) G - T_1 G G^* G. \quad (3)$$

Secondly, let's arbitrarily divide the object field into two parts $G=A+B$ (where A – the field created by $M<N$ object repeaters; B – the field created by other elements; M – the set of reading repeaters; N – the set of intermodulation gratings) and read the referenceless hologram from the incomplete version of the saved template. Let's suppose that behind the field A created by $M<N$ object relays. This is an associative reconstruction mode. Instead of equation (3) there is:

$$\{T_a\} A = T_0 A - T_1 |A|^2 G - T_1 A B^* G \equiv$$
$$\equiv \left(T_0 - T_1 |A|^2 \right) A - T_1 |A|^2 B - T_1 A B^* G. \quad (4)$$

Equation (4) shows that the entire diffraction image (field $(-T_1|A|^2)G$) is reconstructed with an incomplete version of the saved pattern. At the same time, this image has a complex structure. Consequently, the phantom image of the missing part of the field $(-T_1|A|^2)B$ is purely diffractive. Although for the negative hologram this reconstructed field is in the opposite phase to the field of the initial object, lying in the shadow of the phantom image reading beam, it has no distortions and has a real contrast. Moreover, as the power increases, the number of reading transponders M increases, since the amplitude of the resulting image increases proportionally, therefore, the intensity of this image is proportional to M^2.

This key conclusion follows from the optical correlation model of phantom image reconstruction [10].

Reading referenceless hologram by a point source leads to the reconstruction of the autocorrelation image of the template, and not to the usual image that reproduces the spatial intensity distribution over the template. A detailed analysis of the diffraction on the intermod grating set $N(N-1)/2$ associated with the amplitude transmission of the referenceless hologram shows that the reconstructed autocorrelation contains the main image. It does not differ from the set of N «direct» and «inverted» shifted images, but coincides with the object in terms of localization and phase. This coincidence occurs if (and only if) the geometric and wave conditions of the reconstruction strictly reproduce such conditions at the recording stage.

The mentioned experiment assumes the exact reproduction of all initial conditions, including the use of the original diffuser to illuminate the template, as well as its lighting conditions. In other words, associative reconstruction requires:

a) clear reproduction of the boundary field of the object;

b) strict matching of the amplitude transmission of the hologram with the field of the reading object (in practice, matching of the field of the baked reading and the saved template).

Since these conditions are necessary, the following scenario for separating the ghost image from the noise takes place:

– each of the M read relays reconstructs the autocorrelation of an object centered on that relay;

– the main images from the autocorrelation set M, coinciding both in localization and in phase, reinforce each other due to constructive interventions;

– with an increase in the intensity of phantom images ~M^2, the total intensity of reconstruction (the set of M shifted autocorrelations) increases, and ~M increases. This means that, in accordance with the law of energy correlation, the intensity of the halo (halo) associated with the last term of equation (4) should increase more slowly than M. Moreover, starting from some M, not only the relative power of the halo should decrease, but even its absolute intensity.

According to this model, the correlation reconstruction of a phantom image is of a discriminatory nature, which is a consequence of the redistribution of radiation energy by a diffractive referenceless hologram between noise and the phantom image in favor of the image. This means that with a sufficient sample (M/N ratio), the quality of a phantom image can be quite high, in contrast to the preliminary results of experiments [11].

Let's return to the analysis of equation (4). Since the intensity of the template ghost image always increases with increasing ratio $|A|^2/|G|^2 = M/N$, the image intensity of the read fragment decreases due to destructive noise (see the first term on the right side of equation (4)). This means that, in general, the intensity distribution over the entire reconstruction collapses at the boundary between the phantom image and the image of the readout fragment. The brightness imbalance between the two parts of the whole image disappears only in the rather specific case of a negative referenceless hologram, because:

$$T_0 - T_1|A|^2 = T_1|A|^2, \tag{5}$$

that is, when the amplitude coefficients for fields A and B become equal to each other by some amount $|A|^2$ (or M). It is noteworthy that a further increase (or) leads to a brightness inversion, namely, the brightness of the phantom image exceeds the brightness of the (combined) image of the read fragment (5).

It is clear that the brightness inversion effect in the associative referenceless response of a hologram is suitable for detecting small changes in the scene of a stored object. Indeed, since the change area (degree of mismatch of the readout field with the structure of referenceless holograms) is smaller, since the brightness inversion is more pronounced, this is consistent with equation (4), so that detection of small changes can have high efficiency and reliability.

3.3. Resonator architectures based on associative memory error correction. One of the circuit solutions for the associative reconstruction of the stored template is based on the so-called resonator architectures of the HAM, using optical feedback and nonlinearity of the correlation region. This approach is based on a combination of van der Lugt's concept of coherent optics for pattern (character) recognition by appropriate filtering and the possibilities provided by the phase conjugation technique using photorefractive crystals [12].

In the framework of the mentioned approach, a general out-of-axis hologram of an object with a point source of reference is registered. The hologram is read by the object or its incomplete version (with exact reproduction of the geometrical and wave conditions of the recording) and restores the phantom image of the reference source. After that, the reconstructed reference wave is reversed and reads the same hologram in the opposite direction, which leads to the reconstruction of the entire image. This image (main or conjugate) can be divided and, being a separate readout beam, is corrected from errors. The simplest version of this algorithm is implemented by placing a flat mirror in the reconstruction plane of the (real) image of the original source. However, due to the low diffraction efficiency of a hologram, its repeated reading by a backward reference wave provides efficiency of the order of 10^{-3}. This is why, in more efficient implementations, the common mirror is replaced by a photorefractive phase conjugated mirror providing both conjugation and amplification of the reference wave. Of course, this implies a significant complication of the optical arrangement, since the operation of a phase mirror conjugated in the correlation region requires the use of two additional high-power, oppositely directed pump laser beams. The halo in the vicinity of the reconstructed reference source, caused by decorrelation of the read and stored patterns, registration of nonlinearity, scattering noise, can be eliminated by spatial filtering (threshold value) in the correlation

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region using an opaque screen in front of the phase conjugate mirror.

Such filtering is based on the nonlinearity of the correlation region [12]. This associative reconstruction algorithm is represented by the following chain of transformations:

$$G \to \Omega \underset{PC+NL}{\to} \Omega^* \to G^* \text{ or } A \to \Omega \underset{PC+NL}{\to} \Omega^* \to G^*, \quad (6)$$

where PC and NL – phase conjugation (conjugation) and nonlinearity (in the correlation region), respectively; Ω – the reference wave.

Contrary to optimistic forecasts, it should be noted that the associative reconstruction of a whole saved template from its incomplete version is possible only if all geometric and wave conditions of the recording are accurately (say, with interferometric accuracy) reproduced at the reconstruction stage. It assumes the use of the same set of inhomogeneities (surface and volume) representing the object, the same location of the points of the saved image and the referenceless hologram, as well as the lighting mode. Indeed, a referenceless hologram does not preserve the shell of the intensity distribution over the object (as in a conventional photograph), but a unique stationary realization of the ensemble of the spatial amplitude and phase distribution of the object field on the registration plane, that is, it is uniquely determined by the unique amplitude and phase structure of the object. The ensemble of realizations corresponds to all possible spatial distributions associated with an «infinite» set of objects with the same macroform and the same statistics of inhomogeneities, that is, with all objects belonging to a certain class. However, the only unique preserved realization, embodied as a unique speckle pattern, is recognized by referenceless hologram, leading to the reconstruction of the associative response. All other implementations of distributions associated with the same class are evaluated as «alien» by the referenceless hologram, and the phantom image is not reconstructed. Thus, a referenceless hologram operates in the appropriate filtering mode and recognizes an object in the sense of identification, and not in the sense of classification.

Based on the above, it is possible to conclude that an important drawback inherent in standard phantom images is the distortion of the brightness distribution caused by the overlap of two fields (zero and first order) in the image of the read fragment of the saved template. It is clear that in order to eliminate this shortcoming, one should adhere to the concept of encoding/decoding error correction generally accepted in information theory. The central point of this concept is that error detection and error recovery involves the introduction of redundancy. In the case of interest, such redundancy can be implemented by forming an optical twin of the stored template with a corresponding doubling of the number of recorded gratings. This requires that the optical twin be spatially (angularly) separated by the original template, an incomplete version of which is used for reading.

4. Conclusions

In the course of the study, the possibility of a successful solution to the problem of restoring images of acceptable quality using holographic technology was substantiated. It should be especially noted that certain properties of the nonlinear holographic associative memory are implemented not algorithmically, but physically, taking into account the fundamental nonlinearity of all natural processes, which was neglected during the surface (in the first approximation) analysis.

Prospects for the widespread use of HAM in information technology are seen in the improvement of optical material technologies that would be flexible enough for real-time data processing.

Conflict of interests

The author declares that there is no conflict of interest regarding this research, including financial, personal nature, authorship or other nature that could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

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