Advances in
Electronics and Electron Physics

EDITED BY
PETER W. HAWKES

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PREFACE

The four chapters that make up this volume are all concerned, though in very different ways, with image handling, image processing, and image interpretation. The first contribution, which comes from Moscow, should help Western scientists to appreciate the amount of activity in digital optics in the Soviet Union. The extent of this is not always realized, for despite translation programs, some of it is not readily accessible and little is presented at conferences in Europe, the United States, and Japan. I hope that L. P. Yaroslavskii's chapter will help to correct the perspective where necessary.

V. Cappellini needs no introduction to the electrical engineering community; here he surveys the difficult but very active and important fields of digital filtering in two dimensions and source coding. The list of applications in the concluding section shows the wide range of application of these ideas.

The third chapter is concerned with the extremely delicate problem of radiation damage and image interpretation in electron microscopy. For some years, it has been realized, with dismay, that some specimens of great biological importance are destroyed in the electron microscope by the electron dose needed to generate a usable image. One solution is to accumulate very low dose images by computer image manipulation, but a thorough knowledge of image statistics is imperative for this, as indeed it is for other types of electron image processing. This difficult area remained largely uncharted territory until C. H. Slump and H. A. Ferwerda began to explore it in detail: their chapter here gives a very full account of their findings and sheds much light—more indeed than I suspect they dared to hope when they began—on this forbidding subject.

The final chapter, by A. D. Kulkarni, is concerned with yet another branch of this vast subject, in particular with enhancement and image analysis. This should be a very helpful supplement to the basic material to be found in the standard textbooks on the subject.

P. W. Hawkes

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Applied Problems of Digital Optics

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I. INTRODUCTION

Improvement of the quality and information throughput of optical devices has always been the main task of optics. For the majority of applications, today's optics and electronics have, in essence, solved the problem of generating high-quality pictures with great information capacity. Now, the effective use of the enormous amount of information contained in them, i.e., processing of pictures, holograms, and interferograms, has become topical. One might develop the information aspects of the theory of optical pictures and systems on the basis of information and signal theory and enlist the existing tools and methods for signal processing (of which the most important today are those of digital computer engineering). Armed with electronics, optics has mastered new wave length ranges and methods of measurement, and by means of computers it can extract the information content of radiation. Computerized optical devices enhance the analytical capabilities of radiation detection thus opening qualitatively new horizons to all areas in which optical devices find application.

Historically, digital picture processing began at the turn of the 1960s with the application of general-purpose digital computers to the simulation of techniques for picture coding and transmission through communications channels (David, 1961; Huang *et al.*, 1971; Yaroslavskii, 1965, 1968), although digital picture transmission was mentioned as early as the beginning of the 1920s (McFarlane, 1972). By the 1970s it had become obvious that, owing to the advances of computer engineering, it might be expedient to apply digital computers to other picture-processing problems (Vainshtein *et al.*, 1969; Huang *et al.*, 1971; Yaroslavskii, 1968) which traditionally belonged to the domain of optics and optoelectronics. First, publications appeared dealing with computer synthesis of holograms for information display, synthesis of holographic filters, and simulation of holographic processes (Brown and Lohmann, 1966, 1969; Huang and Prasada, 1966; Lesem, 1967; Huang, 1971). Finally, by the middle of the 1970s progress in microelectronics enabled the advent of the first digital picture-processing systems, which found wide applications in Earth resource studies, medical diagnostics, and computer-aided research. The digital processing of pictures and other optical and similar signals is now emerging as a new scientific field integrating theory, methods, and hardware.

We refer to this area as "digital optics" by analogy to the term "digital holography" (Huang, 1971; Yaroslavskii and Merzlyakov, 1977, 1980, 1982), which combines such segments as digital synthesis, analysis, and simulation of holograms and interferograms. The term *digital optics* reflects the fact that along with lenses, mirrors, and other traditional optical elements, digital computers and processors are becoming integral to optical systems. Finally, to complete the characterization of digital optics as a scientific field, one should say that it is a part of the general penetration of computer engineering and digital methods into optical studies, as recently noted by Frieden (1980).

What qualitatively new features are brought to optical systems by digital processors? There are two major ones: first, adaptability and flexibility. Owing to the fact that the digital computer is capable of rearranging the structure of the processing without changing its own physical structure, it is an ideal vehicle for adaptive processing of optical signals and is capable of rapid adaptation to various tasks, first of all to information adaptation. It should be also noted that this capability of the digital computer to adapt and rearrange itself has found application in active and adaptive optics for control of light beams as energy carriers.

The second is the simplicity of acquiring and processing the quantitative data contained in optical signals, and of connecting optical systems with other information systems. The digital signal representing the optical one in the computer is essentially the pure information carried by the optical signal deprived of its physical vestment. Thanks to its universal nature, the digital signal is an ideal means for integration of different information systems.

Digital optics relies upon information theory, digital signal processing theory, statistical decision theory, and that of systems and transformations in optics. Its methods are based on the results of these disciplines, and, similarly, these disciplines find in digital optics new formulations of their problems. Apart from general- and special-purpose computers, the hardware for digital optics also involves optical-to-digital signal converters for input into the digital processor and converters of digital signals into optical form such as displays, photorecorders, and other devices. In the early stages of digital optics, this hardware was borrowed from other fields, including general-purpose computer engineering, computer graphics, and computer-aided design. Currently, however, dedicated hardware is being designed for digital optics, such as devices for the input of holograms and inteferograms into computers, precision photorecorders for picture processing and production of synthesized holograms, displays, and display processors. Digital optics considerably influences trends in today's computer engineering towards the design of dedicated parallel processors of two-dimensional signals.

As an area of research, digital optics interfaces with other information and computer sciences such as pattern recognition, artificial intelligence, computer vision, television, introscopy, acoustoscopy, radio holography, tomography. Therefore, the methods of digital optics are similar to those of these sciences, and, vice versa.

The aim of this article is to discuss the most important problems of applied digital optics as seen by the author, including those of adaptation and of continuity and discreteness in processing pictures and other optical signals.

The first section deals with methods for correction of linear and nonlinear distortions of signals in display and holographic systems and with noise suppression. The emphasis will be on adaptive correction of distortions with unknown parameters and on a means of automatic estimation of these parameters through the observed distorted signal.

The second section is devoted to methods for the improvement of a picture's visual quality and to making preparations for facilitating visual picture interpretation. The term "preparation" was suggested by the present writer (Belikova and Yaroslavskii, 1974; Yaroslavskii, 1979a, 1985) expressly to stress the need for a special processing oriented to the individual user.

The philosophy of the methods described in the first two sections relies upon the adaptive approach formulated in Section I,A, which has three aspects.

First, it is constructed around adaptation to unknown noise and distortion parameters by means of direct estimation of them through observed distorted signals.

Second, for the determination of optimal processing parameters, a new statistical concept of a picture is used that regards the picture as a combination of random object(s) to be interpreted and a random background, together with a new correction quality criterion. This consists in considering that the correction error is minimized on average over a noise ensemble and random parameters of "interpretation objects" (see Subsection II,A,1), while the background is considered as fixed. With this method, adaptation to the background is attained.

Third, the approach envisages adaptation of picture processing to the user, that is to the specific problem faced by the user of the data contained in a picture. As noted above, it is the simplicity of adaptive processing that is one of the basic merits of digital picture processing as compared with analog (optical, photographic, electronic, etc.) methods.

The third section demonstrates how this adaptive approach may be extended to the detection of objects in pictures. This is one of the fundamental problems in automated recognition.

The fourth section discusses the problems of digital holography and, by way of hologram synthesis for information display, illustrates another important and characteristic aspect of digital optics: the need to allow in digital processing for the analog nature of the processed signal, i.e., the need to observe the principle of correspondence between analog signal transformation and its digital counterpart. Such a need exists not only in the digital processing of optical signals, but here and especially in digital holography it is particularly manifest in this system because the digital hologram obtained from a digital (discrete and quantized) signal is at the same time an analog object, an element of an analog optical system, thus a most evident embodiment of the unity of discreteness and continuity.

II. ADAPTIVE CORRECTION OF DISTORTIONS IN IMAGING AND HOLOGRAPHIC SYSTEMS

There are many papers, reviews, and monographs on the correction of distortions in imaging systems (Vasilenko, 1979; Sondhi, 1972; Frieden, 1975; Huang *et al*., 1971; Huang, 1975; Andrews and Hunt, 1977; Gonzales and Wintz, 1977; Pratt, 1978). Their attention is focused on elimination of distortions in systems which either may be regarded as linear, spatially invariant systems with additive and independent noise, or may be reduced to them. Distortions and their correction in holographic systems have not been sufficiently studied. Little attention has been paid to correction of nonlinear distortions, including those due to signal quantization in digital processors, and to suppression of random noise, which is of prime importance in real problems of processing pictures, holograms, and interferograms.

Moreover, the characteristics of distortions and noise, which are required data for their correction and suppression, are usually assumed to be known, although in practical applications of picture processing this is far from being the case, and one must estimate the parameters of distortions and noise directly through the observed distorted signal.

Finally, it should be mentioned that, in the majority of the existing studies of correction, insufficient attention has been paid to the allowance for specific computational methods, peculiarities of digital representation, and processing of signals in digital computers. These problems are discussed in this section.

In Subsection II,A are formulated the principles of the adaptive approach to picture distortion correction, correction quality estimation, and determination of distortion parameters through distorted signals.

Subsection II,B describes algorithms intended for noise parameter estimation through an observed noisy signal: measurements of the variance and correlation function of additive signal-independent fluctuation noise, and of the intensity and frequency of harmonic components of periodic noise in pictures; and estimates of pulse noise and quantization noise parameters, and noise of the "striped" type.

Subsection II,C is devoted to noise filtration: linear filtration with automatic adjustment of parameters for suppression of additive noise of narrow spectral composition as well as "striped" noise, and to nonlinear methods of pulse noise filtration.

On the basis of the adaptive approach developed, methods are proposed in Subsection I,D for the digital correction of linear distortions in imaging systems and those for hologram recording and reconstruction.

Subsection II,E discusses the digital correction of nonlinear distortions, its relation to the problem of optimal signal quantization, practical methods of amplitude correction, and the possibilities of automatic estimation and correction of nonlinear distortions of interferograms and holograms.

A. Problem Formulation. Principles of Adaptation to the Parameters of Signals and Distortions

The solution of the distortion correction problem is built around the assumption that it is possible to define a two-dimensional function $a(x, y)$ describing the output of an ideal system, and the real system may be described by some transform $\mathscr{F}$ converting the ideal signal into that actually observed

$$b(x, y) = \mathscr{F}[a(x, y)] \tag{1}$$

The task of correction is then to determine, knowing some parameters of the transform $\mathscr{F}$, a correcting transform Φ of the observed signal such that the result of its application

$$\hat{a}(x, y) = \Phi[b(x, y)] \tag{2}$$

be, in the sense of some given criterion, as close to the ideal signal as possible.

The choice of approaches to this problem depends on the way of describing signals and their transformations in the corrected systems and also on the correction quality criterion.

1. Description of Pictures and Correction Quality Criterion

According to the fundamental concepts of information theory and optimal signal reception theory, signals are elements of a statistical ensemble defined by the ensembles of messages carried by the signals and random distortions and noise. The distortion correction quality is defined by the correction error of individual realizations of the signal

$$\langle \bar{\varepsilon} \rangle = \langle \overline{\varepsilon_{\mathrm{T}}(a - \hat{a})} \rangle \tag{3}$$

averaged over these ensembles. Here, the overbar represents averaging over the ensemble of random distortions and noise, and the angle brackets represent an average over the ensemble of signals.

For a concrete definition of averaging over the signal ensemble in Eq. (3), it is necessary to have a description of pictures as elements of the statistical ensemble. In studies of picture restoration, the statistical description relies most commonly on statistical models of Gaussian and Markov random processes and their generalizations to the two-dimensional case. As applied to picture processing, this approach, however, is very limited. It is essential in picture processing that pictures are, from the viewpoint of information theory, signals rather than messages. It is the random picture parameters, whose determination is in essence the final aim of picture interpretation, that are messages. These may be size, form, orientation, relative position of picture details, picture texture, etc. Therefore, two essentially different approaches should be distinguished in the formulation of the statistical description of pictures as signals.

In one of them, which may be called a local informational approach, pictures are considered as a set of "interpretation objects" and random background. Interpretation objects involve picture details whose random parameters (e.g., mutual position, form, orientation, number, etc.) are the messages which should be determined as the result of picture interpretation. The rest of the picture, which has no informative (from the viewpoint of the given application) parameters, is the background.

Another approach may be called a structure informational one. In this case, the parameters of the picture as a whole, e.g., its texture, are informative, and the picture cannot be decomposed into interpretation objects and background. For a statistical description of pictures as textures, the above-mentioned classical methods and models of random process theory may be used.

A statistical description of pictures in the local informational approach is more complicated and should be based on a separate statistical description of the interpretation objects and background, and also their interrelations. In particular, this results in the fact that the error [see Eq. (3)] of picture distortion correction should be averaged separately over the random parameters of interpretation objects and random background. In doing so, the correcting transform minimizing the correction error (as averaged over the background) will be also optimal on the average. However, it is usually desirable that the correcting transform be the best for a given particular corrected picture rather than on the average. From the standpoint of the local informational approach, this implies that a conventionally optimal transform with fixed background is desired rather than averaging of the correction error [Eq. (3)] over the random background.

It is this approach that will be studied below. Accordingly, the $\varepsilon_T(a-\hat{a})$ in Eq. (3) will be understood as values of the signal correction error averaged over the set of the corrected picture samples, and angle brackets will be understood as averaging over random interpretation object parameters only.

2. System Description

It is customary to employ for description of signal transformations in imaging and holographic systems models built of elementary units performing pointwise nonlinear or linear transformations of signals and responsible for the so-called nonlinear and linear signal distortions, while random corruptions of the signal are described by models of additive and multiplicative fluctuation and pulse noise.

In accordance with this description, correction is divided into suppression of noise and correction of linear and nonlinear distortions which are solved in the sequence reverse to that of units in the system model.

3. *Principles Underlying Estimation of Noise and Distortion Parameters*

The distinguishing feature of the correction of pictures, holograms, and interferograms is that the characteristics of noise and distortions which are necessary for the construction of correcting transforms in advance are mostly unknown and must be extracted directly from the observed distorted signal. This refers primarily to the determination of statistical characteristics of noise.

At first sight this problem might seem intrinsically contradictory: In order to estimate noise parameters through the observed mixture, one has to separate noise from the signal, which may be done only if noise parameters are known. The way out of this dilemma is not to separate signal and noise for determination of statistical noise characteristics, but to separate their characteristics on the basis of measurements of corresponding characteristics of the observed noisy signal (Jaroslavski, 1980b).

The problem of signal and noise separation may be solved either as a determinate one, if appropriate distorted signal characteristics are known exactly *a priori*, or as a statistical problem of parameter estimation. In the latter case, signal characteristics should be regarded as random variables if they are numbers, or random processes if they are number sequences, and the characteristics determined for the observed signal should be regarded as their realizations.

In this approach, construction of optimal parameter estimation procedures should be based in principle on statistical models of the characteristics under consideration which should be constructed and substantiated specifically for each particular characteristic. Fortunately enough, in the majority of practical cases, noise is a very simple statistical object; i.e., it is describable by a few parameters, and the characteristics of the distorted signal are dependent mostly on the picture background. Therefore, the reduced problem of noise parameter estimation may be solved by comparatively simple tools even if the statistical properties of the measurable video signal characteristics are given *a priori* in a very rough and not too detailed manner. One has only to choose among all the measurable signal characteristics those for which noise-induced distortions manifest themselves as anomalies of behavior detectable in the simplest possible way.