William F. Schreiber

Fundamentals of Electronic Imaging Systems

Some Aspects of Image Processing

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Some Aspects of Image Processing By W. F. Schreiber

Preface

Image processing is an applications area. In this area there are many opportunities to apply art and experience, as well as knowledge from various sciences and engineering disciplines, to the creation of products and processes for which society has urgent need. Without this need, few would be interested in the subject. This point of view motivates this work and has influenced the selection and treatment of topics.

It will be noticed that the word "digital" is not in the title. While much of present-day image processing is implemented digitally, this work is not intended for those who think that image processing is a branch of digital signal processing, except perhaps to try to change their minds.

This book grew out of courses taught at the Massachusetts Institute of Technology by the author and two of his former students, T.S. Huang and O.J. Tretiak. Like the courses, it is primarily intended for electrical engineers and computer scientists who plan to work in the field. It has not proven necessary to spend much time on strictly digital issues, since the students either know that material already or can learn it very easily by themselves. It also has been unnecessary to be encyclopedic, since Pratt[1] has already performed this important service.

What is attempted here is to give the reader enough information about the real world of images and image making so that he can effectively apply the science and technology he already knows to the solution of practical problems. The concentration is on the transmission and reproduction of images of natural objects and documents, monocularly viewed, and usually fixed. The images are intended for viewing by humans, in the normal way that we look at pictures or books, for information, pleasure, or entertainment. The following questions are dealt with:

- What is an image?
- Where does it come from, where does it go to, and what are its characteristics?
- What are the effects on these characteristics of the laws of physics and the properties of contemporary imaging devices and systems?
- How do we perceive images, and how are the design and performance of imaging systems affected by the properties of the observer?

[1] W. Pratt: *Digital Image Processing* (Wiley, New York 1978).

How do we transform effectively between the discrete world of modern data processing and the continuous world of images and observers? To what extent is it possible to reduce the amount of data required to reconstruct images, and how do we deal with the fact that most compression systems alter the objective image parameters?

Finally, I have dealt at some length with applications to graphic arts, a fruitful field to which I have devoted much effort in recent years.

The choice of topics and their treatment arises out of the personal experience of the author, his students, and his associates at MIT and in his consulting practice. This experience has included the development of the *Laserphoto* facsimile system and *Electronic Darkroom* for the Associated Press, the *Autokon*[2] Electronic Process Camera for ECRM, Inc., a real-time two-channel coding system for Sony Corporation, a complete prepress data processing system for a large gravure printer, the development of a number of vidicon, laser, CRT, and CCD scanners, continuous development of computer simulation systems for use in thesis research in image processing, and, most recently, the beginning of a long-term research program in television sponsored by the US broadcasting networks and their major equipment suppliers.

Because of the practical bias of much of this work, we have emphasized those aspects of image processing equipment and algorithms which influence picture quality as perceived by the viewer. It is a chastening experience for an academic to try to get image users, such as printers or TV broadcasters, to accept his computer-processed pictures in place of those made by conventional means. The defects and degradations objected to are not inconsequential. They show that the measurement of picture quality in a meaningful way is not easy. The effect of the characteristics of imaging components, especially cameras and display devices, on the overall performance of systems is generally ignored in the literature, but is actually very large. Our treatment of this subject is not as detailed as desirable, in part because complete knowledge is lacking, but at least we have given the subject significant attention.

The approach to this subject described here has been readily accepted by MIT students, many of whom are still motivated by practical applications, even though the curriculum, like those at comparable schools, is primarily theoretical. Exceptionally bright and alert, they really appreciate accounts of first hand experience, even if (especially if) it does not accord with theory.

Readers will quickly notice that we have a great deal of respect for the work of traditional image-makers. We hope the reasons for this will become evident to those who are more scientifically oriented, as they come

[2] Laserphoto, Electronic Darkroom, and Autokon are trademarks.

to realize the very high standards of quality that are used in these fields, and the degree of skill and diligence employed in their realization. We have made some attempts to translate the words and concepts used by such craftsmen and artists into language more credible to the scientist, but no doubt with limited success.

The preparation of this book would not have been possible without the help of many students and colleagues who supplied material, read innumerable drafts, and offered helpful comments, for all of which I am very grateful. Elisa Meredith and Kathy Cairns served as editorial and administrative assistants, respectively, during the production of the manuscript, and their labors are much appreciated. Of course, the opinions expressed and errors remaining are to be attributed to me alone.

Cambridge, Mass., March, 1986 *W.F. Schreiber*

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1. Introduction

This chapter defines "image" and "image processing" for the purposes of this book. Given these definitions, it becomes evident that exact reproduction is never possible. It is shown that changes in images need not degrade quality, and that it is essential to use perceptually valid quality measures in evaluating processing methods. A generalized image processing system is devised to exhibit the wide range of phenomena associated with imaging apparatus and the correspondingly wide range of knowledge that can fruitfully be brought to bear on the subject. Finally, to make these considerations more explicit, a particular example of a practical imaging system is discussed.

1.1 What is Image Processing?

This book is intended to be written in plain English, in which words have their usual meaning. An example of what we mean by an image is the two-dimensional distribution of light intensity in the focal plane of a camera pointed at a natural scene. Mental "images" will not do; still less a politician's "image" created in the mind of a potential voter by a TV commercial. We do imply visual meaningfulness. Arbitrary two-dimensional functions are not images, nor is a two-dimensional array of numbers, although the latter may represent an image. Processing is the treatment of an image to produce a second image or group of images for some purpose. Making a photographic print from the light distribution in the focal plane is such processing. Recognizing printed English characters in the image of a page is very useful, but is outside the scope of our meaning, as are all types of pattern or character recognition, the work of photointerpreters, and image segmentation or scene analysis except as it may be a step in image coding and reconstruction.

In spite of these restrictions, we have an ample field in which to work. Television, motion pictures, facsimile, and printing together make up an important segment of our economy and one indispensable to education and culture generally. They are all fields that have seen the most modern technology combine with ancient crafts to produce useful and enjoyable products.

Since all these fields have a long history, in the case of printing antedating the discovery of electricity, it is clear that much image processing can be and routinely is done without reliance on electronics and computers. Clearly the use of modern sophisticated methods, in addition to or in place of traditional techniques, must be justified by some advantage of cost, quality, or perhaps convenience. This applies with special force to the replacement of manual by automated operations. While it is true that, on the average, we all get richer when the cost of producing goods and services is reduced, the mindless replacement of people by machines is not only awkward for suddenly "redundant" workers, some of whom may have devoted a lifetime to acquiring the skills suddenly rendered unnecessary, but the savings may be much less than anticipated unless the entire process is first carefully analyzed. A computer is not an artist, and art is the essence of printing good pictures. It often makes much more sense, even economic sense, to design systems to facilitate and augment human capability, rather than to replace it entirely.

Some kinds of image processing make more sense than others. Making a recognizable version of Abraham Lincoln or the Mona Lisa on a line printer may be amusing but hardly useful. Sharpening a chest X-ray by spatial convolution and displaying it on a 512×512 CRT display where it has almost no diagnostic value is a waste of time. Finding the "edges" in an image by repeated correlation operations resulting in a line drawing less representational than can be made by a moderately skilled artist in a few seconds proves very little, although reconstructing a good quality image from compactly coded outlines (even if they are not a pleasing representation) may be very useful indeed. On the other hand, using sophisticated algorithms to produce color separations from which good quality pictures can be printed with inexpensive inks is unquestionably valuable. Coding picture signals so that they can be transmitted with less channel capacity but with subjective quality equal to that obtained by usual methods can be highly advantageous. Taking a corrupted TV image of a planet, received from a space probe, and processing it so that the resulting image is free from defects and that surface features not discernible in the original are made visible is good image processing. Operating on the video signal produced by a television camera so that the image becomes comparable to that from a camera of superior specifications is certainly advantageous. Needless to say, we shall try to concentrate our attention on useful kinds of processing.

1.2 Descriptions of Images

Having distinguished images in our sense from other two-dimensional functions, it remains to describe them in ways that facilitate further processing. In a few special cases, such as test patterns, an algebraic description is possible in which the image intensity can be expressed as a function of spatial and perhaps temporal variables. In the case of graphical images, which we may define as those which can be constructed from a small number of levels, usually two, very compact algebraic descriptions are sometimes possible. More generally, statistical, spectral (e.g., a Fourier transform), or numerical descriptions are required, with the latter particularly valuable, even necessary, for processing by digital machines. We shall devote considerable attention later on to the optimum numerical description of images. The reason for this is that inadequate methods may result in excessive required channel capacity, loss of quality, or both. While only a small amount of capacity is required for a single small monochrome picture, hundreds or even thousands of Megabits per second may be needed to represent high resolution, stereo color motion pictures and perhaps 1000 Megabits for the contents of a Sunday rotogravure section. Economy of numerical descriptions of images is one of the most important topics in image processing.

1.3 Sources and Types of Images

Images are often obtained by viewing natural objects with cameras, either optical, mechanical, or electronic. While the image itself is most often a scalar point function of two variables, it may be three-dimensional, if varying in time, and may be a vector, rather than a scalar, if stereo or color. Holographic systems can have three-dimensional images fixed in time. The object may be a previously made image, such as a photograph or document. Many systems have multiple stages in which the image produced by each stage is the object for the following stage.

In virtually all cases, the image does not perfectly represent the object, in that not enough information is present to permit reconstructing the object exactly. Sometimes this matters, but often it does not. In any event, it should be borne in mind that it is in the nature of images merely to approximate the object and very common for the approximation to be gross. "Exact" reproduction is never possible, on account of the quantum nature of the universe, if for no other reason. This is a phenomenon to be dealt with, not a goal to be sought after with its lack of achievement deemed a failure. Likewise the degree of exactness need not be taken as an index of goodness of imaging systems. We often do not know what scale to use to measure such errors. The quality of images, an important subject, must be related to their usefulness for the intended purpose, rather than the degree to which they duplicate the object.

1.4 Processing Images

Since the output of most processes with which we are concerned is another image, both input and output can often have the same type of description, while the process itself must describe the relation between the two images, usually in mathematical, i.e., algorithmic, terms, either algebraic, logical, statistical, or some combination. For example, a picture may be cropped, enlarged, sharpened, subjected to a nonlinear tone-scale transformation, and noise cleaned. Such a process, or sequence of operations, can be described in terms of an algorithm. We shall always take the point of view that what is characteristic is the algorithm, while of secondary importance is the physical device or system with which the algorithm is implemented.

While many modern image processors, especially those who come to the field from the computer science side, think of image processing largely in terms of computer programs, we shall be willing to evaluate, and perhaps use, any systems that work. These potentially include electronic techniques such as analog and digital hardware, programmable computers, and microprocessors; optical methods, both coherent and incoherent, including conventional optical systems, holographic systems, electro-optical, magneto-optical, and acousto-optical effects; mechanical and photochemical systems, including photography, Xerography and electrostatic systems generally; all kinds of printing processes, both impact and nonimpact; ink jet; and even wood-burning and mosaic tile! The point is that good pictures have been made by all these processes. Some are cheap and repeatable, and describable accurately enough to be both controllable and usable.

1.5 Purposes of Processing

The most common type of processing is reproduction – often at a distance, implying some kind of transmission. Speed and quality in relation to the channel are obvious considerations, and coding an important technique. Storage and retrieval are often involved, with related questions of quality, capacity, cost, access time, etc. The display or recording methods, soft versus hard copy, and the myriad forms of output devices with their individual characteristics must be studied.

Another significant category of processing comprises enhancement and restoration, separate fields or different applications of the same ideas, depending on one's point of view [1.1]. A great deal of attention has been given to this subject by both traditional and modern workers, with the result that a wide variety of very effective methods is available. Recent developments in computer processing foreshadow the early development of cost-effective interactive systems that will enable an editor, i.e., an artist, to manipulate vast amounts of pictorial data easily and quickly to achieve the desired ends.

Although we have specifically excluded pattern recognition and similar techniques from our study, it is appropriate to mention that in certain specialized areas, such as Roman font character recognition, long-standing problems have now been solved to the extent that a number of highly effective machines are commercially available that perform these functions very well. At the present time, the conversion of typed characters to machine code can be done faster, cheaper, and more accurately by machines than by humans. Other types of pattern recognition, such as blood cell classification, chromosome karotyping, and cancer cell detection, are possible but not yet widely used. Interpretation of satellite photos is fairly advanced in some fields, but the goal of completely automated weather forecasting, for example, has not yet been reached.

1.6 Image Quality

Since the images that are the subject of our concern are to be viewed by humans, their quality relates to human perception and judgment. Lacking adequate models of observer reaction, it is generally impossible to calculate precisely, and in some cases even difficult to predict qualitatively, the effect on quality of an alteration in the objective parameters of an image. Finally, since virtually all useful image processing techniques produce such objective changes, subjective testing is required for the evaluation of the comparative merits of different systems. When the quality of a processing system or technique is to be studied, one must, of course, study the quality of the output imagery over the range of inputs and viewing conditions for which the system is designed. It is quite easy to give examples of systems whose rank order depends on the subject matter or the manner in which the output is viewed.

The importance of subjective judgments in television has been recognized for some time. As a result, a great deal of work has been put into contriving experimental setups and statistical methods that give repeatable results. These are admirably summarized in a recent book by *Allnatt* [1.2].

It is not necessary to pretend we know nothing about the observer just because we cannot calculate his reaction exactly. In fact a great deal is known, although many of the classical psychophysical investigations have not measured properties particularly relevant to imaging systems. As the relationship between particular aspects of visual perception and the performance of systems becomes better understood, it has become possible to design new and more useful psychophysical experiments. In some cases, system parameters can be established on the basis of specific measurements.

Some quality factors are self-evident to any technically trained worker. In particular, spatial frequency response can easily be related to resolution and sharpness while temporal frequency response clearly governs motion rendition and flicker. What is not so apparent, especially to scientists and engineers without practical imaging experience, is the great importance of tone rendition. In many if not most cases, it is the most important quality factor. Signal-to-noise ratio (SNR) is another concept familiar to the communication scientist, but neither noise visibility nor the degrading effect of suprathreshold noise follows any simple law [1.3]. Finally, we must deal with a group of factors of everyday overwhelming concern to printers and photographers, but often overlooked by others, namely defects and artifacts. It is almost impossible for laymen to appreciate the degree to which graphic artists abhor defects. In order to achieve the degree of perfection demanded and routinely reproduced by traditional methods, electronic and computer systems require a quality of design and implementation of a very high order. This discipline is not foreign to designers of commercial studio equipment for television and sound broadcasting, but it has to be learned by most other engineers and scientists. The most troublesome factors are geometrical distortion, dirt, streaks and other patterned noise, irregular line or picture element spacing, and nonuniformities of contrast and brightness over the field of view. In color systems, mail-order catalogs for example, color accuracy far beyond that of amateur slide shows or home TV receivers is required, often in spite of rather poor quality paper and ink.

A significant advantage of electronic over traditional systems in the attainment of high quality is the possibility of substantially correcting, in one stage, the distortions introduced in another. An important subject of study is the determination of the theoretical and practical limits to which such correction methods can be carried.

1.7 A Generalized Image Processing System

Figure 1.1 is a block diagram of an image processing system so general that it encompasses a large proportion of systems actually in use. Our purpose in discussing this arrangement is to list the factors that affect the operation of each block and the kinds of knowledge required to analyze and design such systems and their components.

1.7.1 Source/Object

This can be a collection of physical objects or an image produced by another system. It may be self-luminous, or receive light from the surrounding surfaces or from the camera itself in the case of "flying-spot" scanners. It can be fixed or changing, to be viewed in color or achromatically, with one "eye" or two. It can bear a fixed physical relationship to the camera, or there may be relative motion, deliberate or accidental, and change of size and shape with time. The surfaces of the object may be smooth, with various degrees of gloss, irregular, or patterned in such a way as to be described as texture.

It should be noted that the amount and arrangement of the light falling on the object has a profound effect on the quality of the image that is eventually produced. The best results are achieved with diffuse general illumination sufficient to give good signal-to-noise ratio, together with some more