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# Image Restoration and Reconstruction

R. H. T. BATES

and

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OXFORD SCIENCE PUBLICATIONS

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# PREFACE

Image processing is a new science, even though its literature is already huge. It is still too amorphous to permit a definitive treatise to be attempted. What we have produced is a compendium, touching all aspects of the subject with which we are familiar and dwelling upon those we have found to be most useful in scientific contexts and in practical engineering applications. While the majority of the subject matter can be considered soundly established, some of it is tentative. We make no apology for this because of the amount of recently developed material treated here. Advances in engineering and science often come from chance associations of ideas. We have therefore thought it proper to mention our insights, convictions, prejudices (call them what you will!) wherever it seems appropriate. Accordingly, the solid results are interspersed with asides and exhortations which we hope may inspire people to have a crack at the many challenging problems that abound in this science.

Here in New Zealand, pleasantly perched on the very edge of the world, we have found ourselves drawn towards six particular areas of image processing. These are various manifestations of holography, aspects of imaging of importance in medical contexts, astronomical data reduction, restoration of blurred photographs, the very new technique which has come to be called speckle imaging, and the massaging and presentation of satellite imagery. There is, consequently, repeated reference throughout this book to applications in these areas. Furthermore, because we are laying claim to have written a compendium, we have tried to make at least brief mention of all of the scientific and technical fields in which useful advances have stemmed from applying image processing principles and techniques.

While this book is certainly classifiable as a research monograph, it can also be used as a graduate text. It has become customary to intersperse such volumes with 'homework problems'. We are none too sympathetic to this practice in general (except for elementary treatments of basic subjects) and we think it is completely inappropriate for providing the kind of insight which is the essence of image processing. The latter is something of an art as well as a science, relying on intuition based on objectively assessable logical deduction. We hold that the only effective way for a student to acquire what is important of any approach to image processing is actually to implement it, more or less immediately after studying its theoretical background and implications.

Accordingly, we have appended to each chapter in this monograph an extended worked example, relating to particular features of the material covered in the chapter. A suitable student exercise would be either to generate an example of the same kind as one of those presented herein or, more demandingly, to devise a similar example based on an alternative feature of the particular chapter being studied. The software needed for the exercise could be acquired from one of the sources quoted in this book, or be generated in the instructor's laboratory (most probably by senior research students or post-doctoral associates), or even be written by the graduate students themselves.

The material covered by virtually every other graduate-level text on image processing is restricted to what we deal with in a single chapter or, in some instances, in one section of a chapter. This is another sense in which this book can be regarded as a compendium. The subject matter of each of our chapters is summarized in introductory comments which quote the relevant literature, including the available graduate texts. We feel that a graduate student need not have to look any further than these introductory comments to find sources for 'further reading'.

Much of this book is a distillate of the labours of students, colleagues (abroad, as well as in New Zealand at the University of Canterbury and at the Physics and Engineering Laboratory of the Department of Scientific and Industrial Research—PEL/DSIR) and visitors, all of whom we hope will feel adequately acknowledged by their listings in the References. Two who have contributed signally and whom we quote in several of the papers listed in the References, are George L. Berzins (Los Alamos Scientific Laboratory) and R.M. (Bob) Hodgson (Canterbury). John H. Andreae's (Canterbury) detailed criticisms of an early draft of the book helped to correct some of our expositional deficiencies. We are grateful for the unwavering support of Mike A. Collins and Peter J. Ellis of PEL/DSIR. Without Alec L. Cullen's (University College London) initial encouragement and subsequent exhortations, this book would not have been completed. Particular thanks must go to the 1984 postgraduate 'information processing' class at the University of Canterbury whose course assignment was to generate the figures for the worked examples for Chapters IV, V, and VI.

*Canterbury,*
*New Zealand,*
November 1984

R.H.T.B.
M.J.McD.

**Preface to 1989 reprinting**

This reprinting corrects typographical errors in the original printing. Furthermore, we have altered a few statements that are less apposite now than they were in 1984. We have also included an Appendix summarizing the more significant of the advances that have been made during the past four years. Finally, the reader is asked to mentally replace PEL, wherever it appears, with DIT (the DSIR's image processing facility has been transferred from PEL to the Division of Information Technology).

December 1988

R.H.T.B.
M.J.McD.

For

*$D^2EG^2JLP$*

and

*a man of the skies: Edward Roch McDonnell*

# CONTENTS

# I

# SETTING THE SCENE

The purpose of this book is to present the theoretical bases of useful restoration and reconstruction techniques, and to discuss their implementation in the framework of a general image processing system. Everything included here relates directly to experimental methods and/or data reduction procedures that actually work. Specimen processed images, illustrating salient aspects of the text, are included in extended worked examples, one of which serves as a conclusion to each chapter.

The views expressed have been strongly influenced or biased – as is inevitable – by the authors' collective experience in image processing at the University of Canterbury and at the Physics and Engineering Laboratory (PEL), as well as by visits to large and small laboratories around the world. The development of the image processing laboratories at Canterbury and more recently at PEL over the past fifteen years or so has been detached, for largely geographical reasons, from the mainstream of image processing research in the USA. This has led to a somewhat independent approach to a variety of image processing problems. Whenever appropriate, we explain the differences between our approaches and those of other groups and, with the benefit of hindsight, review the ways in which our ideas have evolved.

As far as possible, a narrative style is adopted. This means that in any one section there is minimal reliance on material appearing in later sections. Naturally, there are repeated references to previous sections. Before getting down to the real business of this book, the usual preliminaries must, of course, be disposed of. This is done in the first (i.e. §1) of the sections into which the book is divided.

## 1 Necessary preliminaries

This book is written in sections which run consecutively from §1 to §54. The sections are arranged in groups covering more or less specific topics. These groups are identified in the Table of Contents by the titles of the chapters. Various comments are inserted at the start of each chapter, indicating the overall drift of the subject matter, listing the major applications and summarizing the worked example with which chosen aspects of the text are illustrated. These introductory comments also contain references relevant to the chapter in general and each individual section in particular. References are avoided within the sections themselves, which we believe contributes to the readability of the book.

This chapter provides an overview of image science and introduces ideas which are needed in the body of the work. In §2 image science is defined and the scope of the book stated. In §3 concepts are collected which are required for categorizing blurred images (which are defined in §4) and point spread functions (which are defined in §4 and discussed further in §5).

References are quoted by inserting a name followed by a comma and (a letter and) a number inside square brackets. Multiple references under the same name are indicated by (letters and) numbers separated by commas. Multiple references under different names are separated by semicolons. For references having more than one author, the quoted name is that of the first author. For instance, [Labeyrie, 1, 2: Fienup, 4] refers to the first and second of the items under the name of Labeyrie, and the fourth item under Fienup's name – see the 'References' collected at the end of the book. They are listed alphabetically by the first authors' names. The item number, in square brackets, precedes the name – e.g. the above reference to Fienup is listed as:

[4] Fienup, J.R., Crimmins, T.R., and Holsztynski, W. 1982 "Reconstruction of the support of an object from the support of its autocorrelation" J. Opt. Soc. Am. **72,** 610.

Books, special issues of journals and theses, which are listed separately in the References at the end of this volume, are referred to as above except that B, S, or T prefixes the number – e.g. [Andrews, B1], [Proc. IEEE, S2] or [Gullberg, T1].

The literature encompassing the subject of image science is so extensive that it would be futile to attempt a detailed survey here. This also applies to the more restricted subjects of image restoration and reconstruction. Nevertheless, we think it useful to include in the References various sources which cross-reference much of the published material related to this book. The first source is books which overview aspects of image processing. These are either texts aimed at the (post)graduate level or are collections of related papers. The second source comprises the journals and annual review volumes in which papers on image processing, and in particular image restoration and reconstruction, are most often published. A third source is a list of special issues of some of the aforementioned journals containing up-to-date information and apposite review articles. In recent years, conference proceedings have been a major means of disseminating image processing research results. Many of the conferences, whose proceedings are listed amongst the fourth source, are regular events and much of the material does not get published elsewhere. A fifth source is the series of technical reports published by many institutions with image processing laboratories. Selected reports are usually available on request. It is worth noting that such reports frequently contain valuable practical information which is only published elsewhere in summary form if at all. This often applies to documentation of computer programs or image processing systems. A sixth source is the list of specific references of direct relevance to this book. Finally, we list a few theses containing several worthwhile results, the full details of which cannot be found anywhere else. The seven lists of references are far from exhaustive but they do indicate where, in our experience, the image processing literature can be located.

We emphasize that in Chapters II–IX all the quoted references are collected in the introductory comments to the chapters. References pertaining to §§2–5 are quoted in the two following paragraphs.

For §2, many overviews of image processing, both optical [Bracewell, B1; Dainty, B1; Goodman, B1; Stroke, 1; Vander Lugt, 1] and digital [Andrews, B1, B2, 3; Bernstein, B1; Castleman, B1; Hunt, 2, 4; Pratt, B1; Rosenfeld, B1, B2] are available. See also [Rhodes, B1; Walkup, B1]. The *Manual of Remote Sensing* [Greeves, 1] gives a particularly broad overview of image processing and related subjects. Rosenfeld has for some years published an annual literature review, such as [Rosenfeld, 2]. Sound introductions to rectification are given in [Bernstein, 1; Van Wie, 1]. In addition to the above general treatments, enhancement is overviewed in [Andrews, 2; Billingsley, 1]. Restoration is dealt with in [Andrews, B3, 2; Huang, B1, 2; Sondhi, 1; Trussel, 1]. Good general references for image reconstruction are [Herman, B1, B2, B3; IEEE, S2; van Schooneveld, B1].

The notation and definitions introduced in §3 are discussed in [Andrews, B3; Dainty, B1; Goodman, B1]. These references together with [Huang, 2; Sondhi, 1] are relevant to §§4 and 5. Useful references for the outline presented in §3 of image formation by an imaging instrument are [Born, B1; Bates, 10].

The worked example (Example I) at the end of this chapter illustrates the effects on a particular image of various kinds of degradation that occur in important practical applications.

While details of notation and terminology are introduced whenever appropriate and are summarized in the Glossary, it is convenient to establish some basic conventions here. Equations are numbered consecutively within each section – e.g. (6.8) identifies the eighth equation in §6. Any symbol, $q$ say, which is invoked as an aid to mathematical analysis or to represent a physical quantity is to be thought of as a *number, real* or *complex* according to its definition. Consider *parameters* or *variables*, $z_1$, $z_2$, through $z_n$, which are themselves numbers in the same sense that $q$ is a number. The notation $q = q(z_1, z_2, \ldots, z_n)$ implies that $q$ is a *function* of the variables – i.e. when one or more of the variables changes then $q$ itself varies, in general. The term 'amplitude' implies 'complex amplitude' unless the word 'amplitude' is used in a technically conventional manner –

e.g. 'amplitude modulation'. Consequently, 'amplitude of $q$' is merely longhand for '$q$', but such verbosity is sometimes apposite. Now consider a typical complex number $W$ whose *real* and *imaginary parts* are $U$ and $V$ respectively (remember that both $U$ and $V$ are themselves real numbers). We adopt the following notation and terminology:

$$\mathrm{i} = \text{the pure imaginary} = \sqrt{-1}; \tag{1.1}$$

$$W = U + \mathrm{i}\,V = \text{complex amplitude of } W; \tag{1.2}$$

$$W^* = U - \mathrm{i}\,V = \text{complex conjugate of } W; \tag{1.3}$$

$$|W| = (U^2 + V^2)^{\frac{1}{2}} = \text{magnitude of } W; \tag{1.4}$$

$$|W|^2 = W^* W = U^2 + V^2 = \text{intensity of } W; \tag{1.5}$$

$$\text{phase}\,\{W\} = \arctan(V/U) = \text{phase of } W. \tag{1.6}$$

Note that

$$W = |W| \exp(\mathrm{i}\,\text{phase}\{W\}). \tag{1.7}$$

Abstract notation is abjured throughout most of this book, but it is invoked at times to ensure that some of the more complicated analyses can be concise. Use is made of the notation:

$\in$ denotes membership (in a set or class); (1.8)

$\cup$ denotes union (of sets); (1.9)

$\cap$ denotes intersection (of sets); (1.10)

$\varnothing$ denotes the null set; (1.11)

$\{t_l;\, l = l_a, l_a + 1, \ldots, l_b\}$ denote the set of quantities $t_l$, each of which is indexed by the integer $l$ that runs from $l_a$ to $l_b$. (1.12)

The abbreviations LHS and RHS stand for '(the) left and right, respectively, hand sides (of)'.

## 2 Image science

Since our eyes gather more information than any of our other sense organs, and since the visual cortex seems to dominate the brain, images play a central role in our existence. We perceive space in depth, so that the images formed by the 'mind's eye' are (apparently) three-dimensional. For obvious technical reasons, but also because of deficiencies in our present understanding of perception, only recently has there been much useful manipulation of three-dimensional images in scientific and technological applications. What catches the popular fancy about holography is its capability for reproducing the juxtaposition of objects in space. However, we do not know of any technical use for this fascinating property (there is no sign that holographic movies are going to be a practical proposition in even the moderately near future). Even in holographic interferometry, which certainly is useful, information is displayed two-dimensionally although it is the spatial displacement of objects that is being recorded.

Only two-dimensional images are discussed in this book.

It is useful to define the term *image science* to encompass the recognition of patterns in, the coding of, and the processing of, two-dimensional images. *Pattern recognition* and *image coding* are not treated here.

Information, in particular that present in images, can suffer many kinds of distortion. The word 'distortion' is used descriptively throughout this book. It is also given precise meanings on occasion, as in §3 for instance. This need not lead to any confusion, because the word has numerous (well accepted) connotations in the engineering literature. We feel that the scientifically and technically trained reader should have no difficulty distinguishing our general and specific invocations of the useful portmanteau term 'distortion'.

*Image processing* is concerned with the manipulation of data which are inherently two-dimensional. It often involves removing as much distortion and extraneous contamination as possible from data that are to be displayed pictorially, in order that their valuable information be efficiently coded (for storage or transmission) or the patterns implicit therein can be more easily recognized. The processing can be subdivided into rectification, enhancement, restoration, and reconstruction. *Image rectification* is concerned with spatial transformations that can remove geometric distortions or permit images to be properly registered with respect to each other, for instance in photographic cartography when wide-angle lenses and moving platforms (e.g. aircraft or artificial satellites) are used. *Image enhancement* is concerned with improved presentation (e.g. by noise reduction, compensation for non-linearities of the recording medium, contrast adjustment, edge sharpening) of images whose essential information is clouded but is nevertheless visually apparent before processing. Various enhancement procedures are discussed in detail herein, especially for satellite imagery (of the Earth and the planets).

This book is primarily concerned with *image restoration* and *image reconstruction*. The former term is sometimes equated to image enhancement, which is a pity because it is useful to make a clear distinction between enhancement and restoration. Pictorial information is often made unrecognizable by unwanted distortion, the exact nature of which is unknown *a priori*. Image restoration involves estimating the parameters of the distortion and using them to refurbish the original information. Image reconstruction is concerned with recovering detail in severely blurred images, the causes of whose imperfections are known *a priori*.

Many practical applications of image restoration and reconstruction are quoted throughout this book. All the methods of recovering information are based on the simple 'convolutional model' introduced in §4. The physical basis of the model is discussed in §3.

It is to be understood that the techniques analysed in this book are implemented in digital computers. In principle, many of the techniques could be carried out on coherent and/or incoherent optical benches interfaced to suitable electronic imaging devices. There are enormous difficulties, however, in the way of realizing useful computational accuracies. This is unfortunate because 'optical computing' offers the ultimate in speed (i.e. signals travelling at the velocity of light) and permits 'parallel processing' – e.g. a simple lens 'computes' the whole of a two-dimensional Fourier transform in nanoseconds. Nevertheless, it has not yet proved convenient to carry out other than preliminary computational procedures – e.g. averaging large sequences of two-dimensional data – on optical benches. It is worth distinguishing between 'optical bench computers' and 'electro-optic computers', the latter being composed of digital elements activated by light signals (these may well predominate in the 'guts' of future computers).

To be of practical use, restoration and reconstruction techniques need to be incorporated into a general purpose image processing system. These techniques then become part of a library of compatible image processing tools. The completion of an image processing task involves the selection and utilization of the appropriate tools. A restoration or reconstruction task rarely involves only a single algorithm or technique. It usually consists of several stages and is dependent on integrating a number of enhancement and rectification techniques into an overall systems plan.

The design and contents of an image processing system are thus of direct relevance to our main subject, which is the restoration and reconstruction of images. For this reason we discuss image processing system design in Chapter VII, and program or algorithm categories in Chapter VIII. Our intention is to emphasize that complicated image processing tasks can be carried out successfully with comparatively simple tools, provided they are used in appropriate combinations. Further comments on the purposes and the contents of other chapters are made in §§3 and 5.

## 3 Image distortion and how it arises

Consider quantifiable information, represented by the symbol $f$, existing in a plane which is called *image space*. An arbitrary point in this space is identified by the position vector $\mathbf{x}$. The functional dependence of $f$ on $\mathbf{x}$ is written as

$$f = f(\mathbf{x}). \tag{3.1}$$

The functional dependences of all quantities existing in image space are written similarly.