Digital Image Processing for Remote Sensing

Edited by

Ralph Bernstein

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Edited by

Ralph Bernstein
Senior Engineer and Manager
Advanced Image Processing Analysis
and Development Department
Federal Systems Division
IBM Corporation

Associate Editors

Paul E. Anuta, Associate Program Leader, Laboratory for Applications of Remote Sensing, Purdue University

Ruzena Bajcsy, Associate Professor, Computer and Information Science Department, University of Pennsylvania

Raul Hunziker, Senior Engineer, Federal Systems Division, IBM Corporation

Azriel Rosenfeld, Research Professor, Computer Science Center, University of Maryland

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Preface and Introduction

Historical Perspective

Remote sensing, as its name implies, is the acquisition of physical data relating to an object or feature in a manner which does not involve direct contact in any way. In most cases, the term refers primarily to the sensing of the electromagnetic field. In the past, due to technology limitations, remotely sensed data were derived primarily from the visible portion of the electromagnetic spectrum using eyes and then cameras for sensors. It is interesting to note that a camera was first used to view the earth from a balloon in the 1850's. Since then, there has been impressive progress in sensors, platforms for elevating the sensors to suitable altitudes, and systems for processing the remotely sensed data. Recently, new sensors have been developed, such as the Landsat Multispectral Scanner (MSS), that provide data in the visible and infrared portion of the spectrum in a digital form. The MSS uses an oscillating mirror to scan the earth and detectors to convert the radiance data into voltages which are digitized within the sensor system. Sensors of this type are increasingly being used to provide multispectral image data over a wide spectral region, and new linear array sensors are fast becoming operational.

The last two decades have seen an explosive growth in digital processing technology. This technology has brought about the beginning of a second industrial revolution—one that multiplies man's mental energy, as opposed to increasing his physical energy. This technology, when applied to scientific objectives, and in particular to image processing, has supported the achievement of remarkable scientific results that would not have been possible with earlier available technology. This has been particularly true in the earth, lunar, planetary, space physics, and astronomical observation programs. Concurrently, there has been impressive progress in image technology, transitioning from photography to multiband two-dimensional detector array sensors. It is anticipated that future imaging systems will merge the imaging sensors with the digital processing technology.

This book is a compilation of articles and papers dealing with a dynamic and powerful technology—digital processing of remotely sensed data. The concept is not new; original experiments were conducted shortly after digital computers first became available. However, the digital processing of remotely sensed data in a routine fashion has only recently become practical and common for a number of reasons: computers have become faster and less expensive, sensor technology has transitioned from film systems to solid-state detectors with digital readout, and many investigators have devised new and useful algorithms and techniques to convert data into information.

Digital processing of image data has been applied to many applications. They include biomedical, industrial, surveillance, and earth and space applications. The papers that have been compiled deal primarily, although not exclusively, with techniques that have been developed for the earth and space applications. The earth observation applications that have been extensively developed, and for which image processing has been successfully used, are provided in Table I. It is apparent from this table that the use of remotely sensed data coupled with innovative data processing and information interpretation results in many useful applications that benefit man and his environment.

Organization and Scope

We have attempted to select technical papers and articles that provide a foundation for digital image processing, and have organized the material in a manner that nearly parallels the flow of data from the remotely sensed image to the ultimate user of the data. With reference to Fig. 1, the parts in this book have been structured in the manner shown. This follows the flow of data from the raw, uncorrected image to derived information.

The first part, Image Restoration, deals with methods of compensating for effects which degrade the accuracy of the remotely sensed data by mathematically inverting some of the degrading phenomenon. Various degrading sources are identified, and restoration techniques to compensate for these sources are introduced. The elimination of noise and the compensation of the data for processes that have attenuated spatial frequency characteristics are developed in various papers. Methods to restore data corrupted by image motion blur, noise, and other degrading influences are developed.

Part II, Image Preprocessing and Correction, deals with geometric and radiometric correction of the sensor data and the conversion of the data into products that do not contain intensity errors and geometrically conform to a desired map projection or geometry. The implementation of these operations requires calibration processing and resampling of the image data (computing intensity values between given values). An increasingly important operation also involves mosaicking multiple images into one composite image useful for geological and hydrological analyses. These techniques and others are described in this part, and systems that have been used to implement them are also presented.

Image registration is addressed in Part III. This is a particularly important operation, in that more information can be extracted from remotely sensed data if various image sources are first geometrically registered with each other, that is, are in geometric conformance. Thus, image data in different spectral bands, acquired at different times and scales, from different types of sensors, can be spatially registered to provide data with improved information extraction potential. This part also addresses the technical aspects of cross correlation and the estimates of residual errors after data registration in the presence of noise.

Part IV addresses technology, applicable to the manual extraction of information from an image. Information extrac-

TABLE I

Summary of Applications of Landsat Data in the Various Earth Resources Disciplines[1]

Agriculture, Forestry, and Range Resources	Land Use and Mapping	Geology	Water Resources	Oceanography and Marine Resources	Environment
(1) Discrimination of vegetative types: Crop types Timber types Range vegetation	(1) Classification of land uses	(1) Recognition of rock types	(1) Determination of water boundaries and surface water area and volume	(1) Detection of living marine organisms	(1) Monitoring surface mining and reclamation
(2) Measurement of crop acreage by species	(2) Cartographic mapping and map updating	(2) Mapping of major geologic units	(2) Mapping of floods and flood plains	(2) Determination of turbidity patterns and circulation	(2) Mapping and monitoring of water pollution
(3) Measurement of timber acreage and volume by species	(3) Categorization of land capability	(3) Revising geologic maps	(3) Determination of areal extent of snow and snow boundaries	(3) Mapping shoreline changes	(3) Detection of air pollution and its effects
(4) Determination of range readiness and biomass	(4) Separation of urban and rural categories	(4) Delineation of unconsolidated rock and soils	(4) Measurement of glacial features	(4) Mapping of shoals and shallow areas	(4) Determination of effects of natural disasters
(5) Determination of vegetation vigor	(5) Regional planning	(5) Mapping igneous intrusions	(5) Measurement of sediment and turbidity patterns	(5) Mapping of ice for shipping	(5) Monitoring environmental effects of man's activities (lake eutrophication, defoliation, etc.)
(6) Determination of vegetation stress	(6) Mapping of transportation networks	(6) Mapping recent volcanic surface deposits	(6) Determination of water depth	(6) Study of eddies and waves	
(7) Determination of soil conditions	(7) Mapping of land-water boundaries	(7) Mapping landforms	(7) Delineation of irrigated fields		
(8) Determination of soil associations	(8) Mapping of wetlands	(8) Search for surface guides to mineralization	(8) Inventory of lakes		
(9) Assessment of grass and forest fire damage		(9) Determination of regional structures			
		(10) Mapping linears (fractures)			

[1] From *Mission to Earth: Landsat Views the World*, N. M. Short, P. D. Lowman, Jr., and S. C. Freden, NASA Scientific and Technical Office, 033-000-00659-4, 1976.

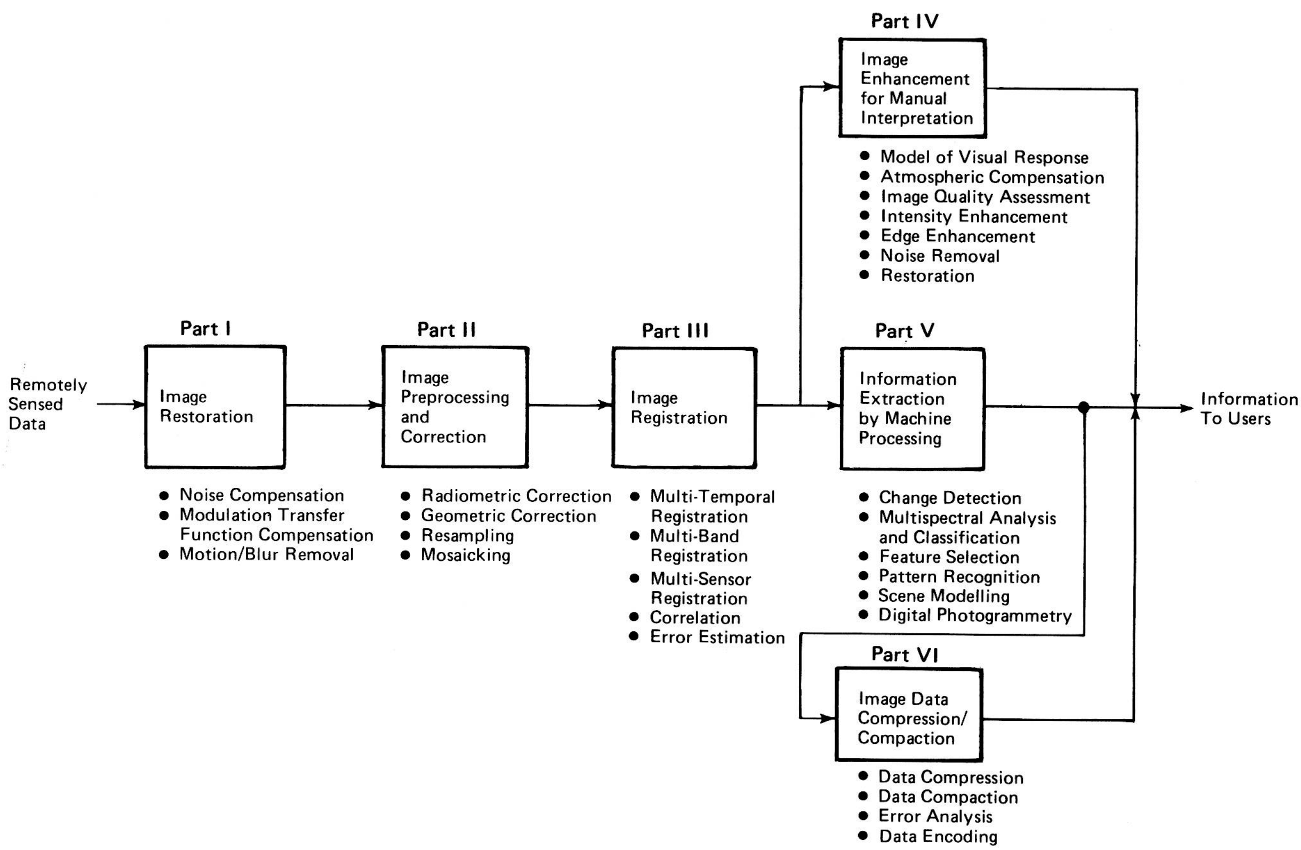


Fig. 1. Organization and content of this book.

tion from image data has been performed in the past by investigators viewing images and extracting information using their eyes and brains. Improvements have come about by developing a better understanding of the human visual response mechanism, restoring and improving the quality of the data, and enhancing the data for visual perception to separate the information from the background. The papers in Part IV develop these concepts and provide a number of illustrative results.

The very recent and important development of techniques for the extraction of information by computers, as opposed to human operators, is addressed in Part V. This development, which is still in its infancy, has resulted in a significant reduction of time and costs and an improvement in accuracy in a number of important applications. The algorithms used in some cases mimic the operation of the human; in other cases they are developed from physical laws and processes. In general, machine processing exploits the fact that computers can examine each image data sample, can discriminate subtle intensity differences, and can perform sophisticated statistical tests on anything from individual samples to large aggregates of data. Papers which discuss the latest developments in such areas as multispectral analysis and classification, digital photogrammetry, pattern recognition, and change detection are included in this part. The algorithms that exist and those that will be developed will have a profound impact on remote sensing.

Part VI encompasses the compression and/or compaction of image data. Generally, image compaction involves the reduction of the number of bits in a scene by eliminating redundant data in a reversable manner. Data compression involves eliminating data to reduce bandwidth/storage requirements and generally is an irreversable process. Various coding techniques and results are presented in this part.

Clearly, the papers that have been selected do not simply or totally fall into the categories discussed. It will be apparent that some papers cover the subjects of more than one part and could have been placed in several of the other parts. However, the papers do provide in one book information that should be useful to the scientist and engineer interested in and involved with remote sensing applications and digital image processing technology.

The book also contains an extensive bibliography of books and papers, covering remote sensing, vision and perception, resolution and image quality, sampling, digital image processing, and multispectral sensing and image analysis. Further, sources of image data are identified to aid scientists and engineers in obtaining remotely sensed data and, in particular, digital data. A glossary has been compiled that provides common definitions of frequently used terms in remote sensing and digital image processing. The Bibliography and Glossary appear at the end of the book.

TECHNOLOGY DIRECTIONS

It is interesting to view the remote sensing and image processing activities on a historical basis and to project future technologies and applications. This provides a basis for understanding technology limitations and trends.

Fig. 2 summarizes the past, present, and future terrestrial and celestial observation and image processing activities. The past and many current activities involve the use of camera systems with photo-optical processing and manual information extraction. Although this will continue to some extent into the future, the trend appears to be towards the use of more advanced multispectral sensors and sophisticated image processing operations to reduce the labor-intensive nature of manual processing. The present approach involves the use of multispectral scanners that provide data in numerous spectral bands, including many outside the spectral response of the human eye. The data, in a digital form, are transmitted to the ground, where high-speed digital processors are used to correct the data and convert them into information products for distribution. Initially, general-purpose computers were programmed to ex-

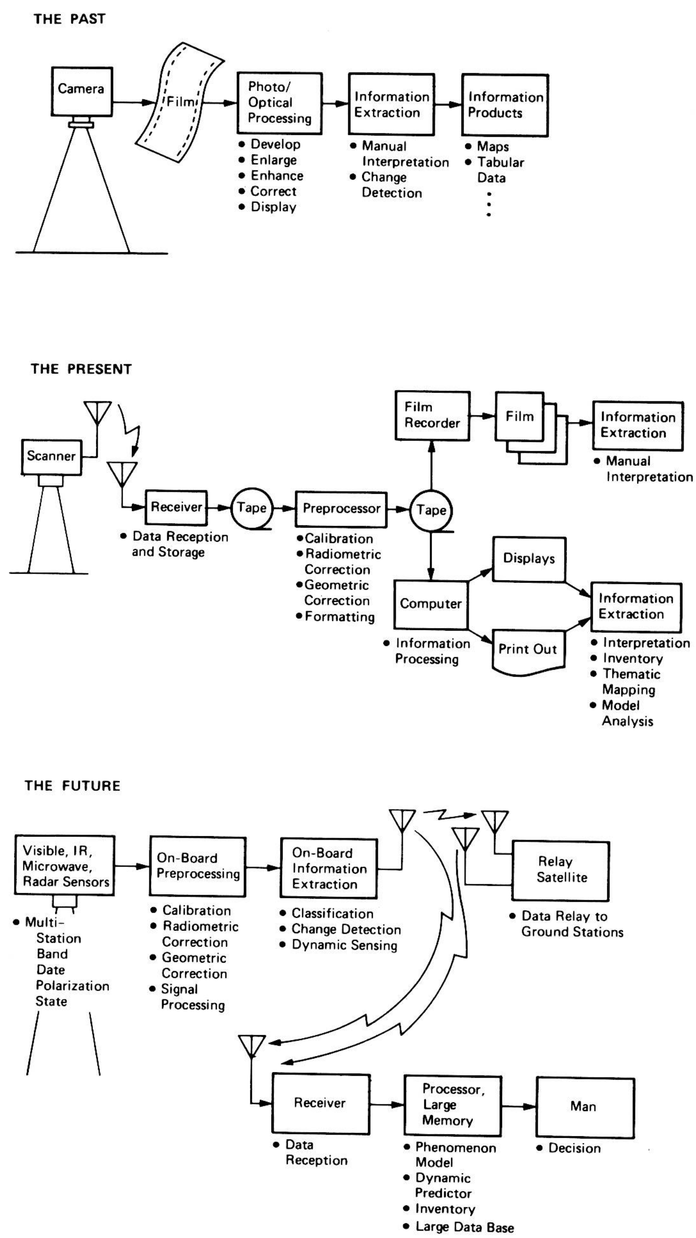


Fig. 2. Remote sensing and image processing: the past, present, and future.

perimentally implement the image processing algorithms. Increasingly, the processors are being specially designed to implement the algorithms, improving the performance and reducing the cost of image processing.

The future approach may go in the direction shown in the figure. Sensors in all spectral bands, including the ultraviolet and microwave, will be used to acquire remotely sensed data. It will be possible in the next two decades to implement selected preprocessing and information extraction algorithms with on-board digital image processing systems and relay the data and information to the ground via communications satellites. This will provide near real-time distribution of information to users so that dynamic events can be detected and monitored.

Clearly, an integrated data collection approach which will provide data acquired at various altitudes from different platforms (space, aircraft, ground) at different viewing angles and times must be and will be designed. A large data base, containing spatial, spectral, and temporal data and information acquired over all geographical areas of interest, will develop. It is anticipated that a data base for terrestrial applications alone could be global in nature and contain over a trillion bits of information. Physical phenomenon models can be structured, which, when provided with past and present data, will allow the prediction of future events more reliably. Thus, the role of man in future systems will be elevated to a higher level and will consist of an interesting interaction with a large data base and phenomenon models, as opposed to the conventional visual image processing of the past.

Acknowledgments

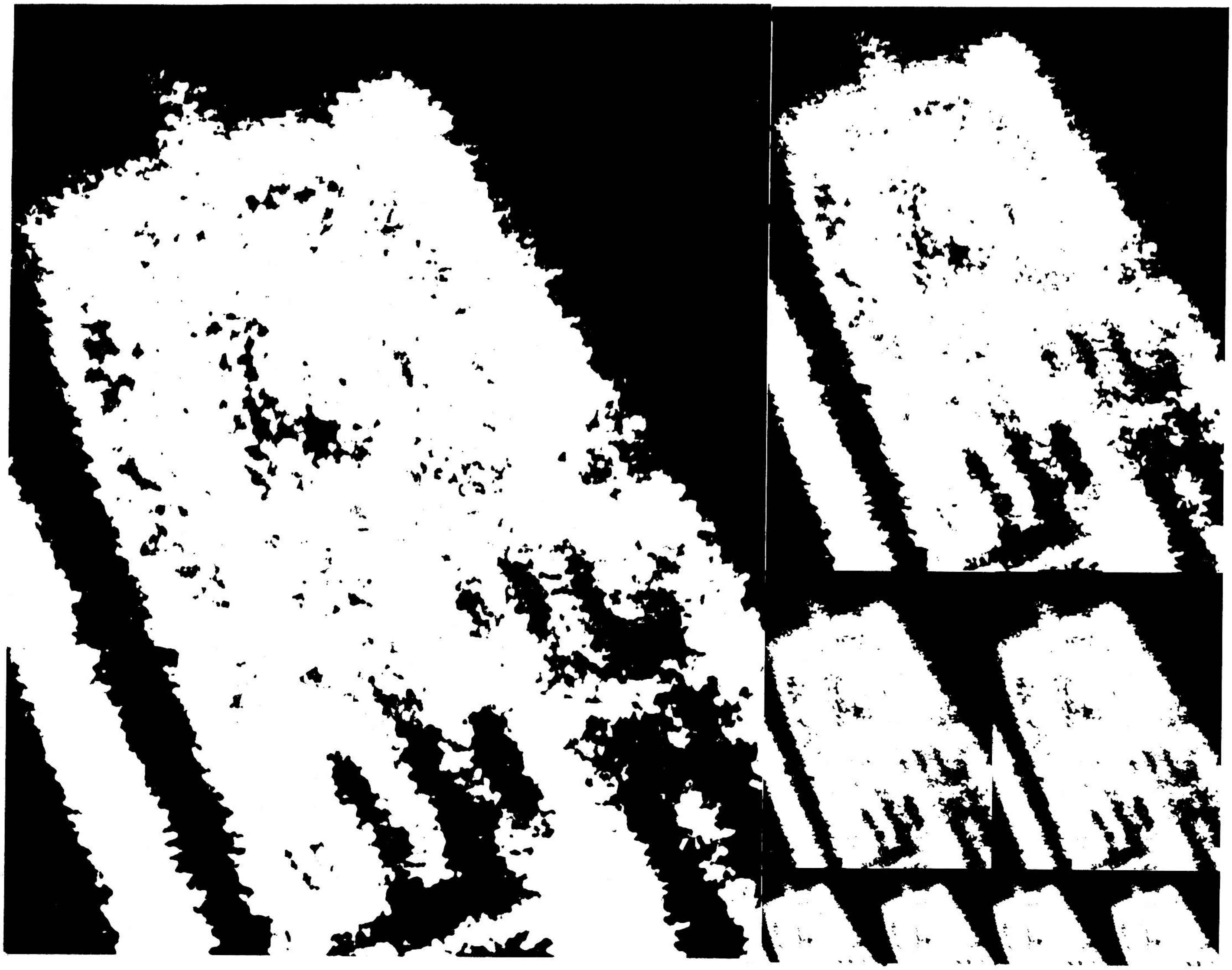
The need for a book on this subject was first recognized by Dr. John W. Rouse, Jr. of Texas A&M, Past President of the IEEE Geoscience Electronics Professional Group. His suggestion was key to the book's preparation. The IEEE, and in particular the IEEE Press, deserve credit for supporting the publication and production of the book. In order to obtain the most representative and best papers in the field, I asked an associate and several leading investigators in the field to assume responsibility for editing the various parts in the book. The papers that have been selected are the result of their analyses and recommendations, and their contributions and help are greatly appreciated. Clearly, acknowledgment and appreciation is due to all of the authors whose papers and articles have been selected to be in this book. Finally, a greal deal of stimulus to the field of remote sensing, and in particular to digital image processing, is the result of the activities of the United States National Aeronautics and Space Administration, and this technology has greatly benefited by the motivation, applications, and support that has been provided by NASA.

Gratitude is due my employer, the Federal Systems Division of the International Business Machines Corporation. I have learned much from a number of engineers and scientists, and IBM management people have encouraged the pursuit of high technology activities and applications that benefit mankind.

This book is dedicated to my wife, Leah, and my family, who have provided me with the inspiration and time to prepare it.

Part I
Image Restoration

Organized by Ralph Bernstein, Editor



Digital Image Restoration: A Survey

Harry C. Andrews
Image Processing Institute
University of Southern California

Introduction

The state of the art in large-scale digital computers has recently opened the way for high resolution image processing by digital techniques. With the increasing availability of digital image input/output devices it is becoming quite feasible for the average computing facility to embark upon high-quality image restoration and enhancement. The motivation for such processes becomes self evident when one realizes the tremendous emphasis man puts on his visual senses for survival. Considering the relative success achieved in one-dimensional (usually time) signal processing, it is to be expected that far greater strides could be made in the visual two-dimensional realm of signal processing.

The areas of space imagery, biomedical imagery, industrial radiographs, photoreconnaissance images, television, forward looking infrared (FLIR), side looking radar (SLR), and several multispectral or other esoteric forms of mapping scenes or objects onto a two-dimensional format are all likely candidates for digital image processing. Yet many non-natural images are also subject to digital processing techniques. By non-natural images one might refer to two-dimensional formats for general data presentation for more efficient human consumption. Thus range range-rate planes, range-time planes, voiceprints, sonargrams, etc., may also find themselves subject to general two-dimensional enhancement and restoration techniques.

The concepts of digital restoration and enhancement are relatively recent in origin due to the need for usually large scale computing facilities. For the sake of semantics we will define restoration to be the reconstruction of an image toward an object (original) by inversion of some degrada-

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tion phenomena. Enhancement will be the attempt to improve the appearance of an image for human viewing or subsequent machine processing. While the above definitions may seem somewhat artificial at this point, hopefully the distinction between restoration and enhancement will become more evident as we progress through the material which follows. (See reference 1 and bibliography in reference 2.)

Restoration techniques require some form of knowledge concerning the degradation phenomena if an attempt at inversion of that phenomena is to be made. This knowledge may come in the form of analytic models, statistical models, or other *a priori* information, coupled with the knowledge (or assumption) of some physical system which provided the imaging process in the first place. Thus considerable emphasis must be placed on sources and their models of degradation – the subject of the discussions that follow.

Enhancement techniques have really resulted from the power and generality provided by the general-purpose computer. Essentially any technique is fair game for enhancement if the resulting image provides additional information about the object which was not readily apparent in the original image. While such a definition in itself appears a little risky, emphasis is placed on the psychophysical aspects of the human visual system coupled with heuristic but mathematically defined operations for image manipulation.[3]

For notational convenience, consistency, and ease of understanding the following format will be established (see Figure 1):

> $f(\zeta,\eta)$ will be the object;
> $g(x,y)$ will be the image;
> $n(x,y)$ will be a two-dimensional sample from a noise process;
> $h(x,y,\zeta,\eta)$ will be known as the impulse response or point spread function (PSF) if the imaging system is linear.

Emerging from the potpourri of methods in use for digital image processing are a set of models in which attempts are made for the restoration of images by the effective inversion of degradation phenomena through which the object itself was imaged. Underlying many of these techniques is a basic assumption of linearity (questionable in itself but of sufficient value for analysis purposes) which provides for the following general model. Let $g(x,y)$ be the image of the object $f(\zeta,\eta)$ which has been degraded by the linear operator $h(x,y,\zeta,\eta)$ such that

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta,\eta)h(x,y,\zeta,\eta)d\zeta d\eta + n(x,y) \quad (1)$$

The system degradation, $h(\cdot)$, is known as the impulse response or point spread function and is physically likened to the output of the system when the input is a delta function or point source of light. If, as the point source explores the object plane, the form of the impulse response remains fixed except for position in the image plane, then the system is said to be spatially invariant – i.e., a spatially invariant point spread function (SIPSF) exists. If this is not the case, then a spatially variant point spread function system results (SVPSF). In this case equation (1) holds, and in the SIPSF case

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta,\eta)h(x-\zeta, y-\eta)d\zeta d\eta + n(x,y) \quad (2)$$

Most researchers have been satisfied with the model of equation (2), with variations such as additive noise, multiplicative noise, etc. Fourier techniques work well in attempting to obtain $f(\zeta,\eta)$ from $g(x,y)$ through the inversion of $h(\cdot)$ of equation (2) due to the Fourier-convolution relationship. Thus, in the absence of noise

$$G(u,v) = H(u,v)F(u,v) \quad (3)$$

where G, H, and F are the Fourier transforms of g, h, f, and the determination of $F(u,v)$ simply requires the inversion of H, if it exists. If the SVPSF model is used, then Fourier techniques are no longer applicable and more general brute force inversion methods must be resorted to for object restoration.

There are three basic approaches which are often used for inversion of either of the two systems as described above. They could be referred to as a) continuous-

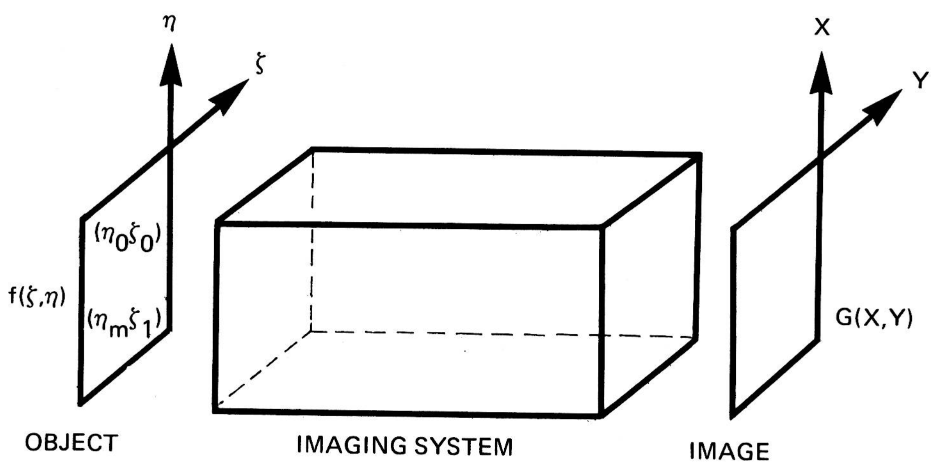


Figure 1. A Linear Imaging System Model

continuous, b) continuous-discrete, and c) discrete-discrete.

The first analysis method looks at the entire image restoration process in a continuous fashion (although ultimate implementation will necessarily be discrete). The second analysis method assumes the object is continuous but the image is sampled and therefore discrete. The third technique assumes completely discrete components and utilizes purely numerical analysis and linear algebraic principles for restoration. In equation form we would have the following imaging models for each of the three assumptions.

a) continuous-continuous:

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta, \eta)h(x,y,\zeta,\eta)d\zeta d\eta + n(x,y) \tag{4}$$

b) continuous-discrete:

$$g_i = \iint_{-\infty}^{\infty} h_i(\zeta, \eta)f(\zeta, \eta)d\zeta d\eta + n_i \qquad i = 1, \ldots, N^2 \tag{5}$$

c) discrete-discrete:

$$\underline{g} = [H]\,\underline{f} + \underline{n} \tag{6}$$

The continuous-continuous model of equation (4) says that the image is simply the integration of the object and point spread function in an analog two-dimensional environment. When the model is put into the computer, the image, object, and point spread function will be sampled by N^2, N^2, N^4 points, repsectively.

The continuous-discrete model of equation (5) implies that the object is continuous (as it would be in the real world) but the sensor defining the image is discrete and already sampled by N^2 points. Thus there are N^2, g_i scalar values and of course N^2, $h_i(\zeta,\eta)$ different point spread functions.

Finally, the discrete-discrete system implies that the object and image are one-dimensional vectors, N^2 long, which represent the original object and image $\underline{f}$, and $\underline{g}$, respectively. The vectors can be raster-scanned versions of two-dimensional functions or any other scanning method such that all N^2 points are obtained. The four-dimensional function $h(\zeta,\eta,x,y)$ is now reduced to a two-dimensional array by the raster scan and thus is a matrix of size $N^2 \times N^2$.

Degradation Sources

There are obviously quite a few sources of degradation in imaging systems, but often they can be grouped into the following general categories and their combinations: a) point degradations, b) spatial degradations, c) temporal degradations, d) chromatic degradations, and e) combinations of the above. To handle the above degradations rigorously in a mathematical sense, and maintaining our assumptions of linearity, we would have to generalize our model in equation (1) to the following:

$$g(x,y,\tau,\omega) = \iiiint_{-\infty}^{\infty} f(\zeta, \eta, t, \lambda)h(x, \zeta,y,\eta,\tau,t,\omega,\lambda)d\zeta d\eta dt d\lambda + n(x,y,\tau,\omega) \tag{7}$$

While such a generalization may be useful for analysis purposes, we will not pursue it further, due to our major concern for spatial systems only. In passing, then, let it suffice to say that temporal and chromatic degradations imply time and color deterioration of their respective axes.

Returning now to equation (1) we see that the "perfect" imaging system would have no noise and an impulse response such that

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta,\eta)\delta(x-\zeta, y-\eta)d\zeta d\eta \tag{8a}$$

$$= f(x,y) \tag{8b}$$

Possibly the first step from perfect imaging is that system which provides no spatial smearing [i.e., no (ζ,η) integration] but induces a point degradation. Thus we might have an impulse response such that

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta,\eta)h(x, y)\delta(p_1(x, y)-\zeta, p_2(x, y)-\eta)d\zeta d\eta + n(x, y) \tag{9a}$$

$$= h(x, y)f(p_1, p_2) + n(x, y) \tag{9b}$$

where $p_1(x,y)$ and $p_2(x,y)$ are geometrical coordinate transformations. The above equation describes imaging systems which do not blur but which introduce a distortion due to a coordinate change. When the imaging system does not introduce a coordinate distortion – i.e.,

$$p_1(x, y) = x$$

$$p_2(x, y) = y$$

we then obtain

$$g(x,y) = \iint_{-\infty}^{\infty} f(\zeta, \eta)h(x,y)\delta(x-\zeta, y-\eta)d\zeta d\eta + n(x,y) \tag{9c}$$

$$= h(x, y)f(x, y) + n(x, y) \tag{9d}$$

This system allows for both multiplicative and additive point degradation effects. The former might be due to film grain, lens or tube shading, or other sensor defects. The latter might be due to electronic scanner effect as well as scattered light and other such phenomena. Equation (9) also provides for some point nonlinear degradations such as gamma curves for film saturation and other intensity distortions if we allow $h(x,y)$ to become a function of the object, $h(x,y,f)$. Unfortunately now, the linearity assumption of our imaging system no longer holds. However, under such generalizations when the impulse response becomes $h(x,y,\zeta,\eta,f)$ we then have a good (albeit nonlinear) model of object-dependent SVPSF phenomena, an example of which might be high energy x-ray imaging where forward scattering (and therefore blur of point sources) becomes a function of the density of the object being imaged.

When our impulse response becomes a function of the object coordinates (ζ,η), we then have some form of smearing or loss of resolution due to the integration of the imaging system over those coordinates. Examples of these so-called spatial degradations are numerous – some of the common of which are a) diffraction-limited optical systems; b) first, second, and higher-order optical system aberrations; c) atmospheric turbulence; d) object-film plane image motion blur; and e) defocused systems.

While the above is certainly not an exhaustive list of spatial degradations, it does provide the flavor of some of the problems faced in image restoration. The models associated with the various defects can be simple SIPSF convolutions or much more complicated SVPSF representations.

The next section addresses the problem of restoring an image which has experienced some form of degradation.

Restoration Techniques

"Restoration techniques" are methods which attempt the inversion of some degrading process the object experienced in being imaged onto some form of hard copy. It goes without saying that the success of the restoration attempt will depend upon how badly degraded the object is, how well one's model fits the physical degrading phenomena the object actually experienced, and how well one's computer algorithm inverts the modeled degradation. Initially it might appear that restoration may in fact be a useless endeavor, since the complexity of object-distorting mechanisms is indeed large. However, there are certain instances in which considerable knowledge is available for correct modeling and in which successful restoration is easily achieved.

In general, restoration techniques can be compartmentalized (for the sake of this discussion) into four general descriptive areas: a) *a priori* knowledge, b) *a posteriori* knowledge, c) signal-processing approaches, and d) numerical analysis approaches. The amount of *a priori* knowledge concerning an imaging system or circumstance obviously plays an important role in the inversion attempt. However, we can often learn about the degradation the object experienced by observing the image itself, and thus the *a posteriori* category. Traditional one-dimensional signal processing attempts have often been utilized successfully in two dimensions, and consequently some of these methods will be surveyed. Finally, more recent numerical analysis techniques have been brought to bear on the restoration effort and are included to provide motivation for possible direction of future methodologies.

A priori knowledge includes a variety of parameters available which might allow for image restoration beforehand. For instance, it may be known that certain geometrical equations of motion or position existed between object and image film plane during exposure, thereby introducing a specific form of motion or coordinate blur (rotation, camera pitch, linear motion blur, coma, tilt, etc.). Algorithms can then be developed for geometrical coordinate transformations for correction of such geometrical blur.[4-7] Other forms of *a priori* models might include assuming the image is formed from a Maxwell Boltzmann distribution[8] and then restoring with a maximum likelihood and maximum entropy algorithm[9,10] or assuming the image is a two-dimensional probability density function and using Bayes theorem for restoration.[11] The above models all have a common thread woven throughout their motivations, and that thread has become known as *positive restoration.* The concept of positive restoration comes from the fact that objects, images, and point spread functions are all non-negative functions.[12]

$$f(\zeta,\eta) \geqslant 0 \tag{10a}$$

$$g(x,y) \geqslant 0 \tag{10b}$$

$$h(x,y,\zeta,\eta) \geqslant 0 \tag{10c}$$

This reality stems from the fact that all optical sensing devices are energy-sensitive and therefore detect non-negative quantities. This fact, though seldom used, has considerable implications in restoration and analysis systems. For instance, the positiveness of g(x,y) forces its Fourier transform to have a deterministic upper limit provided by the Lukosz bound,[13] implying that any restoration technique had better result in a filtered image (estimated object) whose Fourier transform also lies below this bound. The model provided by homomorphic filtering[14] also fits nicely into the positive restoration framework and has been used quite effectively for inherent low frequency illumination removal for image restoration.[15] In addition to positive restoration, one might even consider positive bounded restoration thereby utilizing the *a priori* knowledge that only a finite amount of light could in fact exist at any given point in the original object. This leads to imaging system models in which the assumption of conservation of light flux (lossless imaging) results in an energy equality in image and object – i.e.,

$$\iint_{-\infty}^{\infty} f(\zeta,\eta)d\zeta d\eta = \iint_{-\infty}^{\infty} g(x,y)dxdy \tag{10d}$$

Similarly, such energy conservation assumptions imply that a point source of light should result in no loss of energy or

$$\iint_{-\infty}^{\infty} h(x,y,\zeta,\eta)dxdy = 1 \quad \forall \zeta,\eta \tag{10e}$$

In other words, no matter where the point source of light is in the object (ζ,η) plane, the resulting image (point spread function) always has the same amount of energy.

The above discussion might be the basis for utilizing *a priori* knowledge concerning the effects imposed by an imaging system. However, *a posteriori* knowledge can also play a major role in determining the degradation the object has experienced in being imaged. By *a posteriori* knowledge we mean utilization of the image g(x,y) as an aid in determination of parameters describing the degradation. Obvious examples might include point spread function determination from edges or points in the image that are known to exist in the object.[16] This is often done with test scenes such as resolution charts and point targets (stars and other point sources). Other examples of *a posteriori* image use might include obtaining estimates of the noise variance and possible power spectrum from relatively smooth regions in the image. A third example might be one in which scanner-induced noise (jitter) becomes immediately evident in the Fourier transform of the image although such noise is subtly obscured in the spatial representation of the image.[17] Finally, one might use the Fourier domain of the image to determine and correct for badly defocused imaging systems and linear motion blurred images. While these two degradations may initially seem unrelated, they both have the property that the object spectrum has been modified by functions which have zeros and negative lobes in the frequency domain. In the former case the point spread function is a circular aperture in a SIPSF system with Fourier representation as

$$H(u,v) = \frac{J_1(a\rho)}{a\rho} \tag{11a}$$

where

$$\rho = \sqrt{u^2 + v^2} \tag{11b}$$

In the latter case the SIPSF takes on the form

$$H(u, v) = \frac{\sin a\omega}{\omega} \tag{12a}$$

$$\omega = u \cos\theta + v \sin\theta \tag{12b}$$

Here θ is the direction of motion of the object with respect to the image film plane. Figure 2 represents the concepts. By measuring the zeroes (dark bands) in the Fourier planes it is possible to quantitatively determine the amount of defocus or motion blur and consequently to then remove the effect by traditional filtering techniques.

While the above examples of *a posteriori* use of the image for restoration parameter determination are not exhaustive, hopefully they provide the flavor of such techniques. Naturally parameter determination is important in defining the restoration filter for many of the signal processing approaches which have been commonly employed in image restoration. Traditionally the signal processing approach makes use of the SIPSF model described by equation (2) and repeated here in the absence of noise.

$$g(x, y) = \iint_{-\infty}^{\infty} f(\zeta, \eta) h(x-\zeta, y-\eta) d\zeta d\eta \tag{2}$$

We mentioned earlier the convolutional nature of the above equation and its Fourier equivalent representation in equation (3)

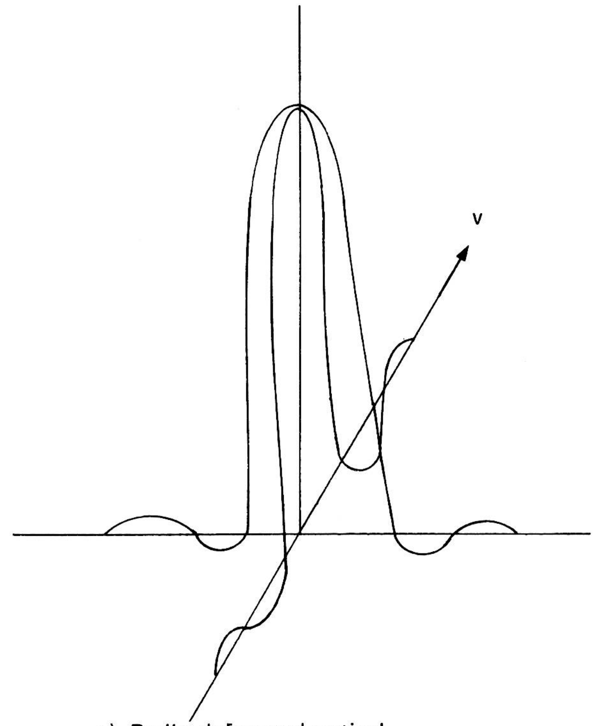
$$G(u, v) = H(u, v)F(u, v) \tag{3}$$

The most immediate filter that comes to mind is the inverse filter which multiplies $G(u,v)$ by $H(u,v)^{-1}$, and then the object $f(\zeta,\eta)$ is obtained by inverse Fourier transforming the result. The restoration filter then becomes:

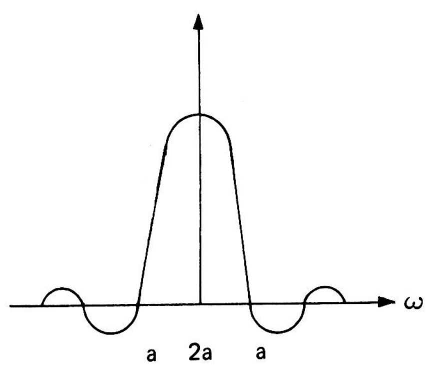
Inverse Filter

$$R(u, v) = H(u, v)^{-1} \tag{13}$$

Unfortunately the inverse filter may not exist due to zeroes in $H(u,v)$ (see Figure 2) and we have ignored the

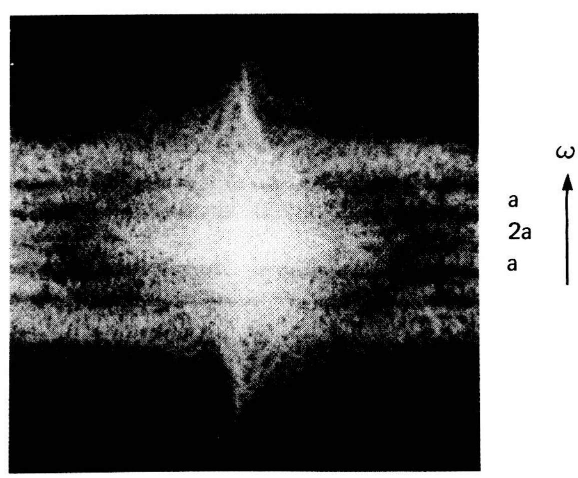


a) Badly defocused optical transfer function, H(u, v)   n



b) Linear motion blur, H(u, v)

c) Bell dummy g(x, y) (moving horizontally)



d) Fourier transform of image

Figure 2. Zeros and Negative Lobe Modulation