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A review of the technical work completed under the Image Processing Program was performed. This review included a description of the program, its objectives, and its evolution; a discussion of a variety of applicable technical approaches used such as bandwith compression, restoration and enhancement of images, visual system modeling, image modeling, and mechanical analysis of images; and an assessment of the scientific and technical accomplishments. Applications and considerations for the future were also → next page
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1.0 EXECUTIVE SUMMARY

1.1 Program Objective and Technical Need

In response to the need for defense systems to acquire, create, and manipulate images, the Image Processing Program was established to address problems associated with the transmission and interpretation of images. Transmission problems centered around the channel bandwidth required for transmitting digitized images. Interpretation problems included the restoration of blurred or noisy images for subsequent human interpretation, the enhancement of images to make important features easier to discern, and machine interpretation of images.

When the program was begun in 1971, it was possible to transmit images at about 3.0 bits per pixel using differential pulse code modulation (DPCM), and at between 1.0 and 2.0 bits per pixel using computationally more complex transform encoding techniques. Restoration of noiseless blurred images was possible through application of deconvolution techniques to space-invariant blurring systems having known point-spread functions. Work on image enhancement was just beginning. Machine interpretation was not available in any useful form, although fairly sophisticated theories of human pattern analysis had been developed by researchers interested in artificial intelligence.

1.2 Program Description and Evolution

The Image Processing Program was begun in August 1971 with funding of work at the University of Southern California and at the University of Utah. Work at USC emphasized bandwidth compression (particularly early in the program) and image restoration, with some attention to the problems of mechanical analysis of images. Work at Utah was concerned primarily with the application of a model of the visual system to problems of restoration and enhancement. Visual system modeling was also applied to encoding images for bandwidth compression, and analogous problems in encoding and restoring speech signals were studied.

Purdue University was added to the program in October 1973. Although Purdue's inclusion reflected increasing emphasis on mechanical analysis of images, much of Purdue's work was on problems of bandwidth compression and image restoration. Relatively little work on mechanical analysis was completed before the program was replaced in 1975 by the Image Understanding Program.

In addition to direct work on the technical problems of image processing, efforts were made to model images and to model the human visual system. Since the effectiveness of various encoding techniques for bandwidth compression depends on the statistical nature of the image, USC included image modeling as an integral part of its bandwidth compression work. Purdue also did some work on statistical image models, but there appeared to be more interest in modeling the characteristics of the object space (background, edges, textures) that are important for mechanical analysis of images. Visual system modeling was concentrated at Utah, where attempts to apply such models led naturally to work on improving them. Utah also incorporated the color response of the visual system into its modeling by adopting a model developed at USC.

1.3 Scientific and Technical Results and Accomplishments

Studies of bandwidth compression produced advances in both transform and DPCM encoding. New methods of transformation were developed; a computationally-efficient DPCM code was found that is nearly optimal for error-free coding of a variety of images; a hybrid transform-DPCM code was developed that would achieve 1.0-2.0 bits-per-pixel encoding at considerable computational saving over transform-only techniques. Detailed analysis of the Fourier transform permitted bit rates for monochromatic images to be reduced to about .4 bits per pixel, and application of visual modeling to color image encoding permitted rates as low as 1.0 bit per pixel. A theoretical relationship was discovered between DPCM codes and transforms, and groundwork was laid for theoretical developments which would eventually describe the relative merits of different transforms.

Advances in image restoration were accomplished for three categories of blurs: space-invariant blurs from a known point-spread function; space-variant blurs from a known point-spread function; and space-invariant blurs from unknown point-spread functions. For known space-invariant blurs, one-dimensional filtering techniques were successfully extended to two dimensions, permitting noise reduction as well as deblurring; and these techniques were refined to the point that fast computational algorithms could be applied with only minor loss of image quality. For known space-variant blurs, it proved possible both to generalize space-invariant techniques to space-variant situations, and to convert images into coordinate systems in which their blurs were space-invariant. For unknown space-invariant blurs, a nonlinear filtering technique inspired by modeling of the visual system permitted estimation of the point-spread function. Furthermore, if a blur belonged to one of three common classes, it proved possible to automatically select the correct class, estimate the function, and restore the image, all without human intervention.

For image enhancement, a technique was developed which permitted selective emphasis of different spatial frequencies. Two pseudocolor techniques were also devised, one in which color was dependent on spatial frequency content, and another in which small gray-level differences were mapped into colors known to be psychologically distinct.

The second pseudocolor technique depended on a substantive achievement in visual system modeling: the development of a color coordinate system in which equal Euclidean distance represents equal perceptual distance. Most of the remaining modeling work merely showed the limits of a useful but obviously simplistic spatial-frequency model. The basic model was revised, but the revised version was never adequately tested.

Image modeling was sufficient as a guide to the development of encoding techniques. Important theoretical foundations were laid when a white-noise model was found inadequate, although a more general model was not developed until after the end of the Image Processing Program. In other research, Purdue and USC obtained conflicting results on autocorrelation models, and an attempt to model object space was frustrated by difficulty in discriminating between edges and textures.

Although work on mechanical interpretation of images never progressed beyond a preliminary stage during the life of the program, there were three significant results: theoretical extension of an edge-detection system to color images; development of a method for detecting boundaries between areas differing only in texture; and creation of an algorithm for finding closed boundaries by detecting regions that are homogeneous with respect to image statistics.

1.4 Applications and Considerations for the Future

Research performed under the Image Processing Program showed that it is possible to compress image bandwidth significantly and to restore images subjected to a variety of degradations. Substantial computation is necessary, and that computation requires either significant amounts of time or complex, specialized hardware. Thus the feasibility of applying compression and restoration techniques depends on the relative costs of time, hardware, and bandwidth, as well as on the image quality required for a particular application.

Comparatively little was accomplished in the mechanical interpretation of images or in the development of image models and visual system models. Research in mechanical interpretation has been continued under the Image Understanding Program. There has also been some work on image modeling, oriented toward the semantics and syntax of the object space. Research is still needed on statistical models independent of object-space interpretation: The statistical assumptions underlying many image processing techniques are known to be inaccurate, and better models should lead to improved techniques. More research is also needed in modeling the human visual system. The simplistic models used during the program were very productive in inspiring useful image processing strategies, and improved models may be expected to inspire still more.

One area of research completely ignored during the program is the measurement of image quality. Comparisons between image processing techniques were made by looking at the results and making subjective judgments. In some cases the images used may not be of appropriate quality to show the limits of the processing techniques; and the subjective judgment of an investigator may not always reflect the presence or absence of image characteristics important for particular applications. The most esthetically pleasing image, for example, may not be the one in which it is easiest to discern critical objects such as camouflaged military installations.

1.5 Program Impact and Assessment of Technology Developed

The technology developed by the Image Processing Program has found direct defense application in remotely-piloted vehicles and in intelligence. The chief non-defense application has been in the space program. Although these specific applications are useful, the primary impact of the program has been on subsequent research and development. Prior to the program, image processing research was scattered.

The program gave that research visibility, creating a recognized specialty that attracted new researchers. A momentum was thus created: Research continues in the absence of a specific program to support it. The consequence is a steadily increasing technological base that can be drawn on in developing defense systems that exploit imagery.

2.0 PROGRAM OBJECTIVE AND TECHNICAL NEED

2.1 Defense Problem Addressed

The Image Processing Program can be perceived as the response to a major trend in modern defense systems: the acquisition, creation, and manipulation of images and image-like data. Visual imagery is essential to a wide variety of tasks, from guiding a vehicle past obstacles, to identifying objects such as ships or planes, to seeing patterns of deployment on which to base command and control decisions. Often it is not practical to depend directly on the visual system of a human observer to produce the necessary imagery. It may be necessary to store an image for more detailed analysis than is possible during the time that the scene remains unchanged, as when looking for camouflaged objects. It may also be necessary to communicate an image to those who are not present; the extreme case is that in which it is not practical for any human observer to be present, as on surveillance satellites or on remotely-piloted vehicles in dangerous places.

The two major problems associated with images are transmission and interpretation. If the image is transmitted as an analog signal in the manner of television, it is subject to noise. However, any simple system of digitizing the image can produce a faithful rendition only if a very large number of bits are used, making transmission a time-consuming affair and rendering real-time imagery impossible. A method of bandwidth compression (i.e., of reducing the bit rate required for transmission) is needed.

Interpretation may be performed by a human, in which case transmission noise combines with distortion produced by the camera's optical system, with motion blurs, with atmosphere effects in long-range images, etc., to make the task difficult. It is necessary to restore the image to something near its undegraded state. Furthermore, since the human visual system is itself limited, it may be desirable to enhance the image to make details more readily apparent.

Alternatively, interpretation may be performed mechanically, either by imitating human visual processes or by using special interpretation schemes only a machine could perform. Just as human interpretation may require restoration and enhancement, machine interpretation may require preprocessing of the image before the interpretation algorithms are applied.

2.2 State of the Art at Program Inception

By 1971, two coding systems had been developed for bandwidth compression. Bell Laboratories, working on its PicturPhone project, had developed differential pulse code modulation (DPCM), a system in which the difference between the actual and expected intensity of a pixel is encoded. The expected intensity is derived from one or more adjacent pixels. DPCM systems transmitting at 3.0 bits per pixel had become common laboratory demonstrations. An alternative system, pursued at the University of Southern California under NASA sponsorship, had achieved acceptable transmission at between 1.0 and 2.0 bits per pixel. The USC system treated the digitized image as a matrix with highly inter-correlated entries. An orthogonal transformation was applied to the matrix, decorrelating it to reduce redundancy. By transmitting the transformed matrix, or some part of it containing most of the image information, it was possible to reduce the number of bits transmitted while keeping degradation of the reconstructed image within acceptable limits.

NASA had also been involved in work on the restoration of images. In order to compensate for degradations inherent in video cameras carried to the moon, workers at the Jet Propulsion Laboratory of the California Institute of Technology had developed techniques for deconvolving the image from the known point-spread function of the imaging system.

Almost no work had been done on enhancing images, as opposed to restoring them to their predegraded state. The distinction between restoration and enhancement was just emerging at the time, and work on enhancement had been limited to simple strategies such as gray-level equalization.

Work on the mechanical analysis of images had achieved little in the way of practical results. There was some fairly sophisticated theoretical work among those interested in modeling human perceptual processes, with attention to the merits of template matching, feature extraction, and analysis-by-synthesis. Algorithms for scene segmentation were beginning to be successfully implemented, and machine recognition of limited sets of figures such as printed letters had been achieved. In general, long computation times were required for only modest results.

3.0 PROGRAM DESCRIPTION AND EVOLUTION

The Image Processing Program, which extended from August 1971 to September 1975, developed digital techniques for the solution of transmission and analysis problems. Work on bandwidth reduction was heaviest near the beginning of the program. Most of the attention to analysis was concerned with restoration and enhancement for human interpreters, with work on these areas continuing at a near constant level for the duration of the program. Mechanical analysis was not emphasized, but it received increased interest near the end of the program. The problems associated with mechanical analysis led naturally to the replacement of the program in 1975 by the Image Understanding Program. In an attempt to produce automatic image interpretation systems, the new program added the skills of the artificial intelligence community to the signal processing skills tapped by the original program.

3.1 Contractors

Three contractors were involved in the Image Processing Program. The University of Southern California participated from the program's inception in August 1971 under the direction of William K. Pratt. The University of Utah, which had an ongoing graphics program, was also funded in August 1971 through change orders to its graphics contract. A new contract was awarded in July 1973 with Thomas G. Stockham, Jr. as principal investigator. A smaller effort was funded at Purdue University in October 1973. Paul A. Wintz and David A. Landgrebe directed Purdue's work at the beginning, with Landgrebe being succeeded by Thomas S. Huang in 1974. Purdue was phased into the Image Understanding Program in February 1975. The other contractors continued in the original program until its termination in September 1975. USC became a full participant in the Image Understanding Program, and Utah was given additional funds to complete work in progress.

3.2 Technical Approaches

3.2.1 Bandwidth Compression. Most of the work on encoding images for efficient transmission was performed at USC. While there was some attempt to improve DPCM systems, major emphasis was placed on orthogonal transformation methods, a relatively new approach originated at USC. Transformation techniques require compromises between bit rate reduction, computational complexity, and quality of the reconstructed image. Hence the effort was to find transformations which represent superior compromises. Also significant was the combination of transformations with DPCM in hybrid techniques.

The choice of an appropriate transformation depends on the structure of the particular image being transmitted. An alternative to looking for an optimum transformation for a class of images is to generate a universally applicable code that will keep image degradation within acceptable limits regardless of image characteristics. While there was some work at USC along that line, Purdue pursued it directly with a system for error-free coding. Rather than considering transforms, work at Purdue was concerned with choosing a suboptimum variable-length DPCM code that would be computationally efficient and that would remain nearly optimum regardless of image statistics.

Digitizing an image produces quantization errors, and additional quantization errors are introduced when an image is transformed and the results are expressed digitally. Since the original image is autocorrelated, its statistics were used in predictive reconstruction strategies. The objective was to improve on the center of the quantization interval as an estimate of the original pre-quantized signal value.

Encoding color images creates special problems, in that three values must be transmitted for each pixel. Alternative systems of choosing those three values, such as American television's YIQ and standard red-green-blue, were compared for sensitivity to noise and quantization errors. Work at Utah attempted to apply a model of the visual system to improved encoding of color images.

3.2.2 Restoration and Enhancement of Images. Three general strategies for restoring images are distinguishable. At USC, one-dimensional techniques such as Wiener filtering were extended to two-dimensional images. At Utah, techniques derived from a model of the visual system were applied. In practice, the Utah techniques overlap considerably with the USC approach. They differ primarily in Utah's use of homomorphic filtering: A nonlinear (usually logarithmic) transformation of image intensities is performed prior to the application of standard filtering techniques. Purdue followed a third approach, developing a projection method for solving image-restoration equations. In that method, a trial solution is projected onto the set of hyperplanes formed by the equations, and a new trial solution is generated; the process is iterated until a satisfactory solution is reached.

A special problem for restoration is that of space-variant blurs. Standard deconvolution techniques apply only to space-invariant point spread functions. One approach to space-variant blurs is to transform the image into a coordinate system in which the blur is space-invariant, then restore it after deblurring. Another is to specify the full distortion function as a matrix and to use the generalized inverse of that matrix to deblur the image. The latter approach, while more general than the former, suffers from computational difficulties associated with near-zero values in the inverse, which result in amplification of noise or quantization error. Attempted solutions include transformation to eigenspace, filtering of eigenvectors, and recursive restoration with human intervention.

Enhancement strategies tend to depend more consistently on ideas about how the visual system works than do restoration strategies. However, similar approaches were used, such as filtering of spatial frequencies. Some consideration was given to pseudocolor, a technique for improving the discriminability of fine differences in monochromatic images by making them different colors. Different spatial-frequency filters for the three primary colors were tried in an effort to improve on more conventional translation of different gray levels into different colors.

Work on enhancement and restoration included efforts in a variety of related areas, including compensation for deficiencies in the color dyes of films, reconstruction of two-dimensional images from a series of one-dimensional projections, and enhancement of images through the detection of objects or edges. A substantial effort was made to apply models of color vision to restoration and enhancement of color images, extending the principles already applied at Utah for monochromatic images. At Utah there was also work on the restoration and enhancement of speech signals, which provided some insights into processing techniques being applied to images.

3.2.3 Visual System Modeling. The work on restoration and enhancement performed at Utah drew on models of the visual system for its inspiration, and efforts were made to extend and improve such models. The two key features of models developed at Utah had been proposed by Stockham, Utah's principal investigator, prior to the start of the Image

Processing Program. Those features were to model the eye's response to light as the logarithm of light intensity, and to assume the existence of one or more spatial-frequency filters as the result of neurological inhibition. Models were subjected to two kinds of test. In the more rigorous test, a model was used to generate an explanation of perceptual illusions, and the inverse of the model was applied to images in an attempt to cancel such illusions. A less rigorous check was to use a model to predict satisfactory image enhancement strategies.

The modeling performed at Utah began with monochromatic images. Later extensions to color incorporated work performed at USC. The modeling at USC was concerned with color scaling and with relating equal brightness curves to the standard CIE Chromaticity system.

In addition to the primary efforts in modeling, work was performed at Utah on a modification of the Land retinex theory to render it computable, and at USC on attributing some of the spatial-frequency filtering of the eye to its optics rather than to the visual nervous system.

3.2.4 Image Modeling. Much of the work on encoding and on restoration implicitly worked with statistical models of images. At USC, although there was little formal image modeling, autocorrelation models were tested for use in coding systems. Utah developed a very simple model related to its concept of spatial frequency filters in the visual system: The image was decomposed into a low spatial frequency component, representing illumination, and a high spatial frequency component, representing object reflectances. Only at Purdue was there a significant explicit effort to model images. An attempt was made to see whether the real images produced by Earth Resources Satellites (ERTS) conformed to the Markoff processes commonly assumed. For purposes of image encoding, images were modeled as random-increment processes. There was also an attempt to decompose images into background, texture, and edges, with the idea that encoding and restoration would work better if the fundamental parts of the image were recognized and treated separately. The decomposition model, of course, also qualifies as an effort at mechanical analysis of the image.

3.2.5 Mechanical Analysis of Images. Although attention to automatic interpretation of images increased toward the end of the program, no contractor became heavily involved. USC used the largest variety of techniques: signal detection for deciding on the presence or absence of a known object in an image assumed to have an object; threshold analysis and contour tracing for the detection of edges; and feature analysis for the identification of textures. At the other end of the scale, Utah used only template-matching as a pattern-recognition technique, and that technique was applied only to speech analysis for the purpose of identifying words or speakers. Purdue used statistical analysis to define homogeneous regions, with edges defined as the boundaries of regions. Purdue's approach contrasts with that of USC, where edges were detected directly and did not necessarily create closed boundaries. Purdue also used feature analysis for the identification of hand-printed letters.

3.2.6 Support Projects. All three contractors developed image-processing hardware and software systems. At Utah some work continued on artificial-photography-like graphics, with some potential for these being a source of image models. In general, however, the work consisted of improving display techniques and developing algorithms for rapid computations of the types required by the work being performed in encoding and restoration.

4.0 SCIENTIFIC AND TECHNICAL RESULTS AND ACCOMPLISHMENTS

4.1 Bandwidth Compression

Studies of transformation approaches to encoding images led to both development of new techniques and refinement of those previously studied. Two noteworthy new techniques were considered. One which was fully developed was the slant transform, which used multi-level basis functions instead of the bi-level functions used in Hadamard and Walsh transforms. The slant transform achieved bit rates of 1.0 to 2.0 bits per pixel, comparable to rates achieved with Hadamard and Walsh transforms. A second new transform attempted to gain some of the advantages of the Karhunen-Loeve transform, while avoiding the latter's computational complexity. Karhunen-Loeve is a theoretically optimum transformation for images describable in terms of second-order statistics. The new transformation used a triangular matrix to achieve equally good decorrelation. Although computationally simpler, the inverse of the triangular transformation did not lead to a unique solution, and that difficulty was not overcome.

Analysis of the already-familiar Fourier transform led to the greatest gains in bandwidth compression. The use of separate codes for the magnitude and phase components of the image permitted transmission at about .4 bits per pixel, at the cost of considerable computational complexity.

There were two significant theoretical developments in the area of transform coding. One was the discovery that DPCM codes can be treated as a class of transformations. The other, which did not come to fruition until after the completion of the program, was a theoretical structure able to explain the advantages of cosine transformations, which are currently preferred by researchers in the area.

The use of hybrid transform-DPCM codes was an entirely new development. Although these codes do not improve on the compression available from transform-only codes, they share some of their immunity to transmission errors while avoiding some of their computational complexity.

Work on error-free coding was concerned with avoiding computational complexity, since an optimum variable-word-length DPCM code was already known. Three classes of suboptimal codes were developed and tested on several images. No one code was found that was consistently better than all the others. However, a code was identified which, while never best, was always a close second. Rates of 2.5 bits per pixel were achieved for images requiring a theoretical minimum of 2.4 for error-free coding.

Slight gains were made in studies of quantization, with adaptive codes and predictive reconstruction permitting bandwidth reduction of about .1 bit per pixel. Work on color encoding did not produce a clearly-preferred physical coordinate system, but translation into a coordinate system based on equal apparent color differences permitted encoding with as little as 1.0 bit per pixel.

4.2 Image Restoration

A blurred image may be modeled mathematically as the superposition of an ideal image and a blurring system, or point-spread function. If the point-spread function is space-invariant, blurring all parts of the image equally, the superposition integral becomes a convolutional integral.

Pseudo-inverse restoration of images was extensively developed. The convolutional integral is converted to a set of linear equations through quadrature solution, and the linear equations are solved for the original image by taking the pseudo-inverse of the matrix representing the point-spread function. Fast computational methods were developed, at the expense of loss of image quality near the edges.

Theoretical development showed that pseudo-inverse restoration is closely related to Wiener filtering and to other solutions constrained, for example, by the requirement that the restored image be everywhere positive. In general, one-dimensional techniques such as Wiener filtering were successfully extended to two dimensions, providing noise reduction as well as deblurring.

Fourier transformation had previously been applied to deblurring, since Fourier analysis maps convolution into multiplication. It was shown that Fourier analysis transforms the image into its eigenspace. Restoration techniques working directly in the eigenspace were developed. Considerable success was obtained with singular value decomposition, although human intervention was required to determine the level beyond which using near-zero eigenvalues produced more distortion than the gain in sharpness was worth. Since it was possible to work in the eigenspace of space-variant blurs, the approach can be seen as an extension of Fourier mapping to the situation in which the blurred image cannot be modeled as a convolution.

The attempt to change space-variant blurs to coordinate systems in which the blurs are space-invariant also met with considerable success. Appropriate coordinate systems were found for a variety of common blurs, making rapid space-invariant computational techniques applicable.

The projection technique developed at Purdue was also found to be applicable to space-variant blurs. It could be used even when the point-spread function lacked an inverse, and it was possible to incorporate constraints into the solution, such as a requirement that no intensities be negative. Satisfactory results were obtained with on the order of a dozen iterations.

All of the techniques described above require a priori knowledge of the point-spread function. A technique not requiring such knowledge, applicable to space-invariant blurs, was developed as a consequence of research on homomorphic filtering. Fourier analysis maps convolution into multiplication, and the logarithmic transformation used in homomorphic filtering maps multiplication into addition. By averaging across small segments of an image thus transformed, it was possible to compute a result that represented the average blur plus the average unblurred image. An unblurred image of a similar scene could be used to estimate image statistics, after which it was possible to solve for the blur. The system worked well for magnitude but not for phase. However, for a restricted set of common blurs of known phase, it proved possible to select the correct deblurring function automatically without human intervention.

4.3 Image Enhancement

With image restoration, success can be estimated in terms of some criterion such as least-squares error from the original. No such criterion has been established for enhancement, so that practical achievements are hard to assess. Nonetheless, there appear to be three significant achievements in this area.

The first achievement relates to the application of a principle. Work on homomorphic filtering, employing concepts from visual system modeling (Section 4.4), demonstrated the ability to emphasize selected characteristics of monochromatic and color images. Even if one were to reject some of the judgments made as to what constituted improvement, the techniques should be applicable to other criteria.

The second and third achievements are concerned with the use of pseudocolor for images that were originally monochromatic. Image interpreters sometimes complain that pseudocolor merely maps a nearly imperceptible difference in gray level into an equally slight difference in color. However, work on using different spatial-frequency filters for the three primary colors produced images in which previously-hidden edge detail is prominent. Another strategy, designed for mapping gray-level differences into colors known to be perceptually distinct, was used successfully in improving diagnosis from X-ray images.

4.4 Visual System Modeling

Most of the work in modeling the visual system cannot be said to have achieved any significant theoretical advances. The logarithmic response of visual receptors to light was a well-established approximation. The idea of spatial-frequency filtering adopted by signal processing people prior to the Image Processing Program was a useful generalization and simplification of inhibition effects discovered in physiological studies of the eye. Work performed during the program showed the limits of that generalization. As evidenced by attempts to cancel spatial contrast illusions by applying the inverse model to images, the spatial frequency notion was much too simple. It handled such illusions in slowly-varying images, but it broke down wherever edges were present.

The model was extended by replacing low- and high-pass filters with a series of bandpass filters. Each filter had an automatic gain control, so that the frequency content of an image tended to be equalized. The application of the modified model to enhancement produced the ability to selectively emphasize chosen aspects of an image (Section 4.3), an effect particularly obvious when the model was extended to color. However, no evidence was presented to support the model. The enhancement work is in a sense counterevidence: If the visual system contained completely effective automatic gain controls, the observer would not be able to tell that the relative frequency content of two images differed. Naturally, one could assume imperfect gain controls. However, the presence of even imperfect controls would reduce the effectiveness of an enhancement strategy based on duplicating their function, and their existence cannot be inferred from the success of that strategy.

In the realm of color vision, it was possible to develop a transformation that maps any physical tristimulus values into a coordinate space in which equal Euclidean distance corresponds to equal apparent difference between colors. Such a system has potential for the creation of error measures for image restoration that are based on perceptible rather than physical distortion. The color model was later incorporated into the bandpass model described above.

Work on attributing the low-pass filtering characteristics of the eye to its optical system had only begun by the time the program ended. The model has since been used in successful color coding techniques. If those techniques depend on the subtle differences between locating the low-pass filter in the optics and locating it in the nervous system, the result would be of considerable theoretical significance. Psychophysiological research has consistently indicated that lens and cornea characteristics are not the factors limiting acuity in the normal eye except when the pupil is large.

4.5 Image Modeling

Conflicting results were obtained in work on modeling image processes. At USC, autocorrelation models were supported, with third-order predictors providing good results. At Purdue, it was found that Earth Resource Satellite images did not conform to such models.

A white-noise, causal model based on Kalman filter concepts was found to have limited utility. The foundations were laid for a more general model based on partial differential equations, although the work did not come to fruition until well after the completion of the program.

An independent-increment model was found adequate as a basis for error-free coding (Section 4.1). Work was also begun on a decomposition model, in which the image was viewed as consisting of background, edges, and textures. However, there was difficulty in discriminating between edges and textures, frustrating the aim of compressing bandwidth by using different encoding methods for the three components.

4.6 Mechanical Analysis of Images

Most of the work on mechanical analysis can be regarded as preliminary. In some cases, researchers appear to have been simply familiarizing themselves with the area. An example is the application of signal detection theory to detection of the presence of objects, which predictably produced machine decisions far superior to those of human observers. There was some important theoretical work, such as the extension of the Hueckel edge-detection operator to three-space to permit edge detection in color images. Most of the attempted applications, such as actual edge detectors, were primitive from a practical standpoint, although serving to increase their creators' understanding of the problems to be solved.

Two particularly significant results did emerge. One was the development of a system for detecting boundaries between areas differing only in texture. The boundary detector itself was limited, but an important gain was made in understanding the nature of textures and how to describe them. Of more immediate practical value was the development of a region-growing algorithm. That algorithm decides whether to include new points in an established, object-like region by performing tests of statistical homogeneity. The edges of the regions always form closed boundaries. It was possible to obtain a hierarchy of regions, thus varying the resolution of the processed image, by changing the criterion for homogeneity. Although the algorithm tested only means and variances of intensities, the general technique is adaptable to any useful statistic, such as a good measure of texture.

5.0 APPLICATIONS AND CONSIDERATIONS FOR THE FUTURE

The accomplishments of the Image Processing Program include improvements in bandwidth compression and in the ability to restore degraded images. Despite some concern with topics such as fast computational algorithms, research was not in general directed toward studying the feasibility of applying the techniques developed to practical problems. Nonetheless, some preliminary considerations of feasibility may be discussed, and suggestions may be made concerning future research.

5.1 Feasibility of Applying Image Processing Techniques

In general, there is a three-way trade-off among bandwidth compression, the quality of the transmitted image, and the computational load involved in encoding and decoding the image. Most of the bandwidth compression schemes studied were not oriented toward real-time implementation. However, in most cases computational time can be saved if the hardware is made sufficiently complex to allow parallel processing. Thus the question of feasibility of bandwidth compression depends on the relative costs of time, hardware complexity, and increased channel bandwidth. Such costs, as well as the image quality required, are dependent on particular applications.

Restoration and enhancement techniques similarly involve computational complexity, with trade-offs much like those for bandwidth compression. The chief difference is that restoration and enhancement appear particularly applicable to selected important images obtained at high cost (e.g., images from space probes or satellites), so that real-time computation is less important. Furthermore, since the computational load is at the receiver, problems associated with the weight or reliability of complex sensor hardware are not applicable.

5.2 Recommendations for Research and Development

5.2.1 Automatic Interpretation of Images. Relatively little work was done on mechanical analysis during the Image Processing Program. Hence, the lack of significant results cannot be interpreted as an indication of unfeasibility. On the contrary, some intriguing first results were obtained. Since practice was well behind theory in automated pattern recognition, it is appropriate that the Image Understanding Program called upon researchers in artificial intelligence as well as in signal processing to concentrate their efforts in this area.

5.2.2 Image Modeling. The Image Understanding Program includes work on modeling the semantics and syntax of the object space. That kind of modeling is appropriate to automatic interpretation problems. However, there still remains work to be done in making models of the image which do not require object-space interpretations. For example, a number of image processing techniques employ assumptions about the stationarity of the image as a random process. Since images are clearly not stationary random processes, many such techniques might be improved if nonstationary models of images were developed. Similarly, most techniques use assumptions leading to linear statistical estimators such as Wiener estimates and minimum mean square predictors, and the consequences of nonlinear models should be explored.

5.2.3 Visual System Modeling. Despite the weaknesses of models of the human visual system developed during the Image Processing Program, those models were very productive in suggesting coding and enhancement techniques. An interdisciplinary modeling effort, in which people working on physiological and behavioral aspects of the visual system interacted directly with people working on mathematical models, should be able to produce greatly improved models.

These models may in turn suggest a variety of useful image processing techniques.

5.2.4 Measuring Image Quality. Research is needed to develop metrics for evaluating the quality of decoded, restored, or enhanced images. The lack of any objective evaluation criterion is a serious difficulty in judging image processing techniques. Assessments presented in this document depend largely on intuitive judgments: The final image seems natural-looking, or there is little visible difference between an original image and its reconstruction.

Intuitive judgments can serve only as a rough guide. Their inadequacy is revealed by examination of Figures 5-1 and 5-2. In Figure 5-1, the top image has clearly been less accurately reconstructed than the bottom image, yet the two reconstructions are of similar quality. It is unclear whether the technique used for the bottom pair could reconstruct a sharp image any better than the technique used for the top pair. In Figure 5-2, comparison of the results of the three enhancement methods is essentially an esthetic judgment, since it is not clear how one would decide which of the images would be most useful for any practical purpose.

The development of appropriate metrics would permit processed images to be evaluated with respect to the presence or absence of characteristics needed by humans for the interpretation tasks they must perform. The metrics could also be applied to the original images used in research, for the purpose of indicating which images are of appropriate quality to provide genuine tests of the techniques being studied.

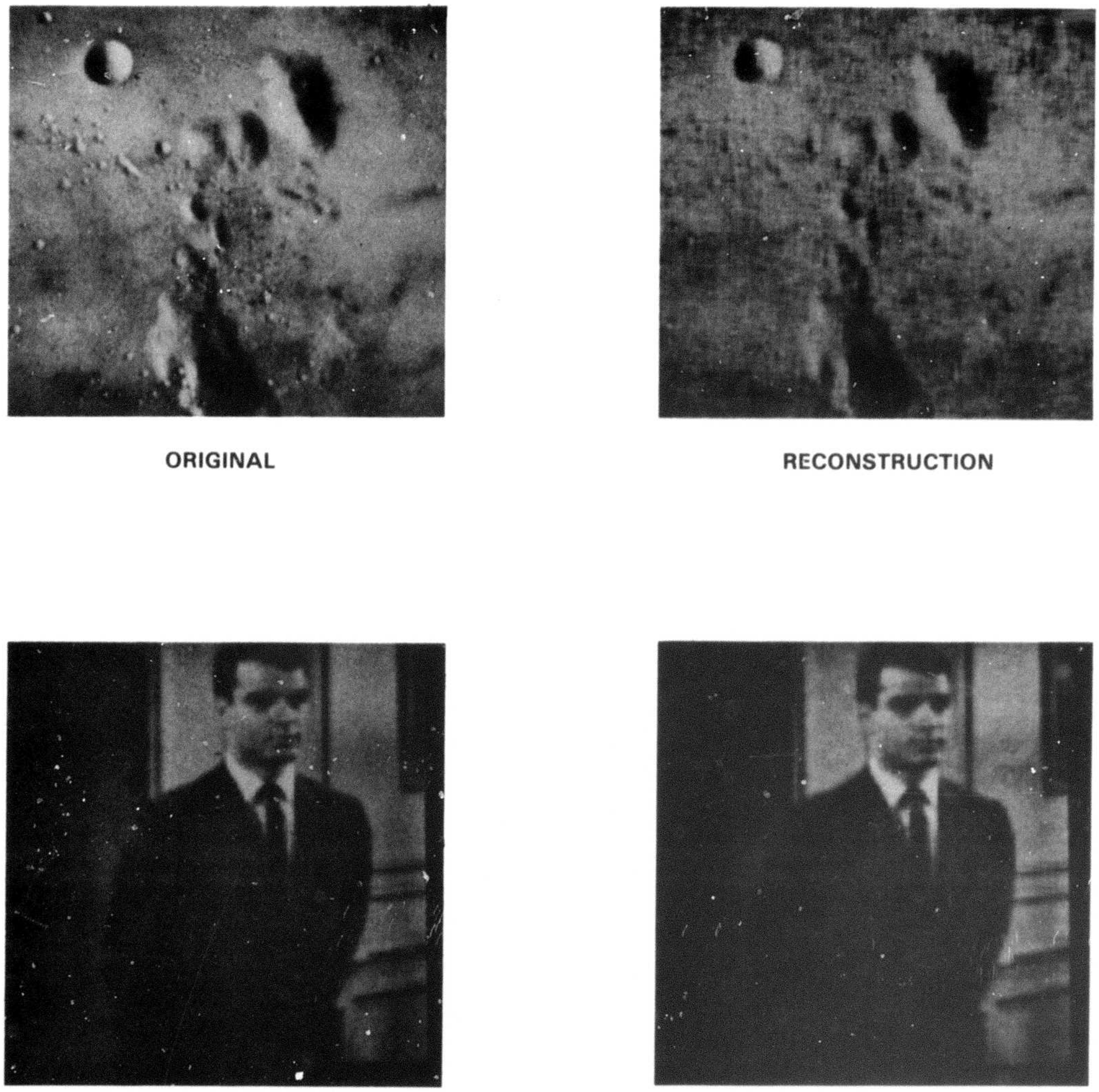
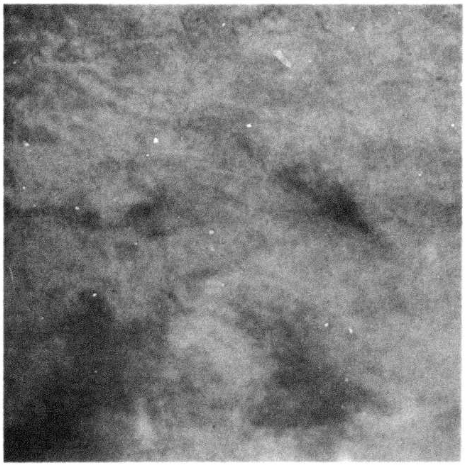
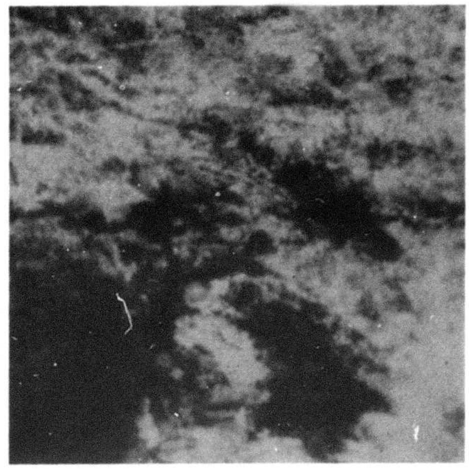


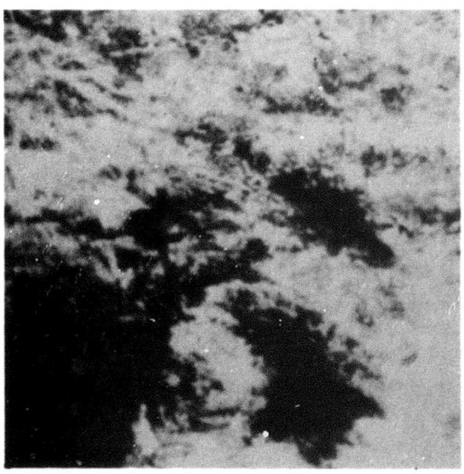
Figure 5-1 Reconstructions of Two Images Differing in Sharpness.



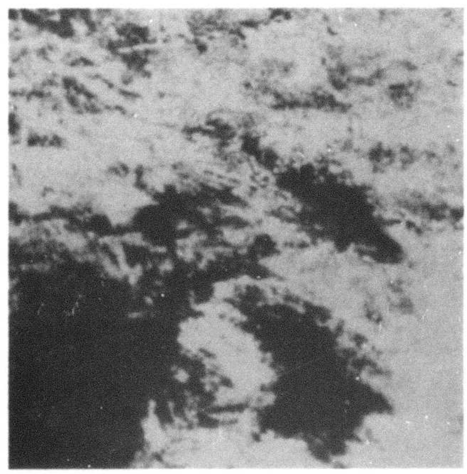
ORIGINAL



GRAY-LEVEL EQUALIZATION



GRAY-LEVEL EXPONENTIATION
(Method 1)



GRAY-LEVEL EXPONENTIATION
(Method 2)

Figure 5-2. An Original Image and Three Enhancements.

6.0 PROGRAM IMPACT AND ASSESSMENT OF TECHNOLOGY DEVELOPED

The technology developed by the Image Processing Program has found two direct defense applications, one in remotely-piloted vehicles (RPV's) and the other in intelligence. With RPV's, the problem is to transmit an intelligible image to the distant pilot. The strategy has been to preprocess images for purposes of enhancement, then to transmit the image. Both DPCM and hybrid transform-DPCM codes are used to reduce the required transmission bandwidth. Intelligence applications are also concerned with bandwidth reduction and with image enhancement, and there has also been some use of image restoration techniques.

The chief non-defense application of program-developed technology has been in the space program. NASA support of image processing techniques predates the Image Processing Program. Improvements in techniques have been directly applicable to transmitting and restoring images from space probes and satellites.

Although specific techniques have been useful, the major impact of the Image Processing Program has been on subsequent research and development. Prior to the program, research on image processing was scattered and could not be regarded as a major activity within the disciplines of electrical engineering, optics, or signal processing. As the research sponsored by the program gained recognition within the technical community, new researchers became interested in image processing problems. By the time the program ended, image processing was an important area of research, able to attract technical personnel and to obtain funding from diverse sources. The Image Processing Program had been responsible for the creation of a kind of "critical mass," and the result has been a continuing flow of research. That research has contributed to a constantly increasing base of science and technology that can be drawn on in developing defense systems that exploit imagery.

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